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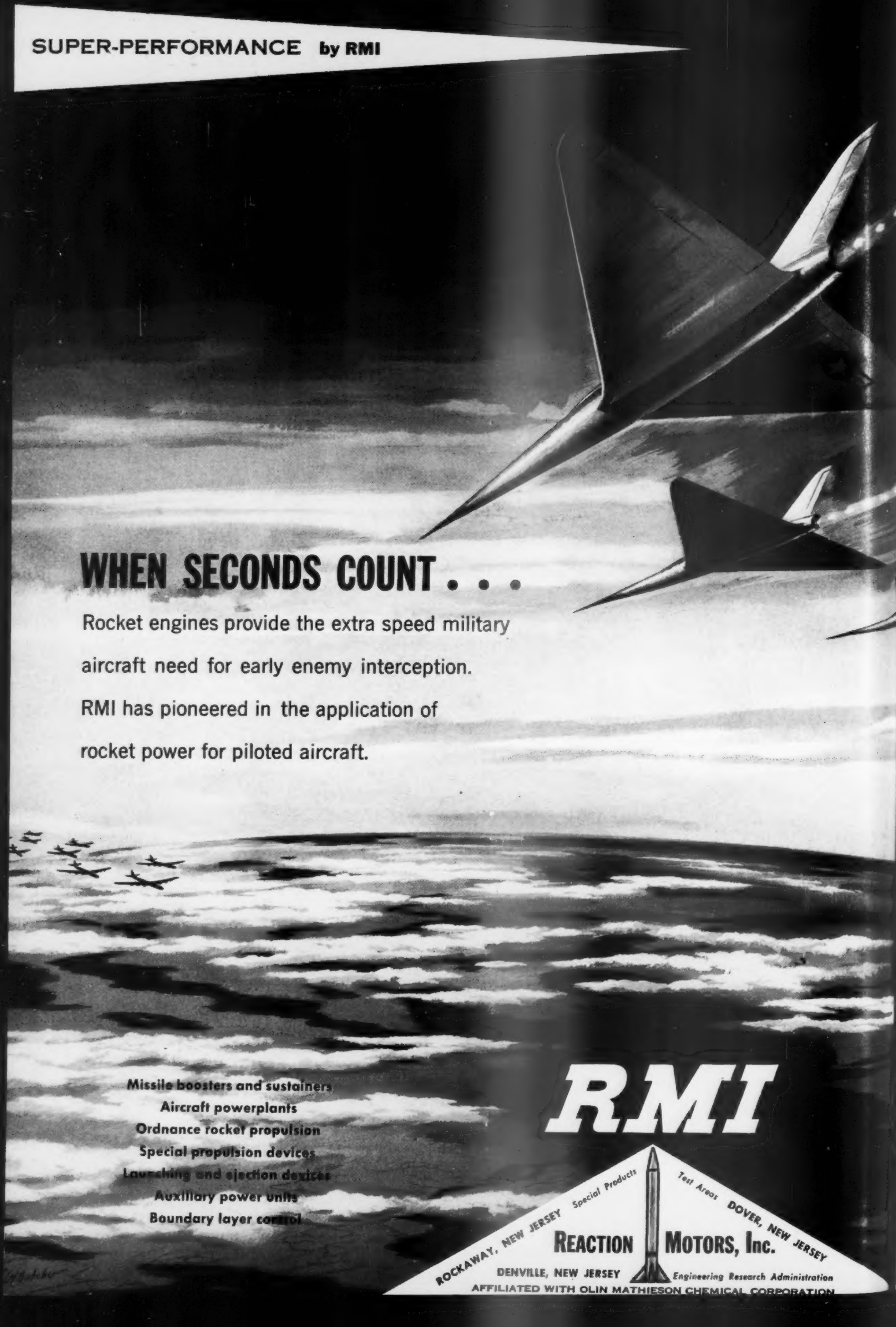

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Jet Propulsion, the Journal of the American Rocket Society, is devoted to the advancement of the field of jet propulsion through the publication of original papers disclosing new knowledge and new developments. The term "jet propulsion" as used herein is understood to embrace all engines that develop thrust by rearward discharge of a jet through a nozzle or duct; and thus it includes systems utilizing atmospheric air and underwater systems, as well as rocket engines. Jet Propulsion is open to contributions, either fundamental or applied, dealing with specialized aspects of jet and rocket propulsion, such as fuels and propellants, combustion, heat transfer, high temperature materials, mechanical design analyses, flight mechanics of jet-propelled vehicles, astronautics, and so forth. Jet Propulsion endeavors, also, to keep its subscribers informed of the affairs of the Society and of outstanding events in the rocket and jet propulsion field.

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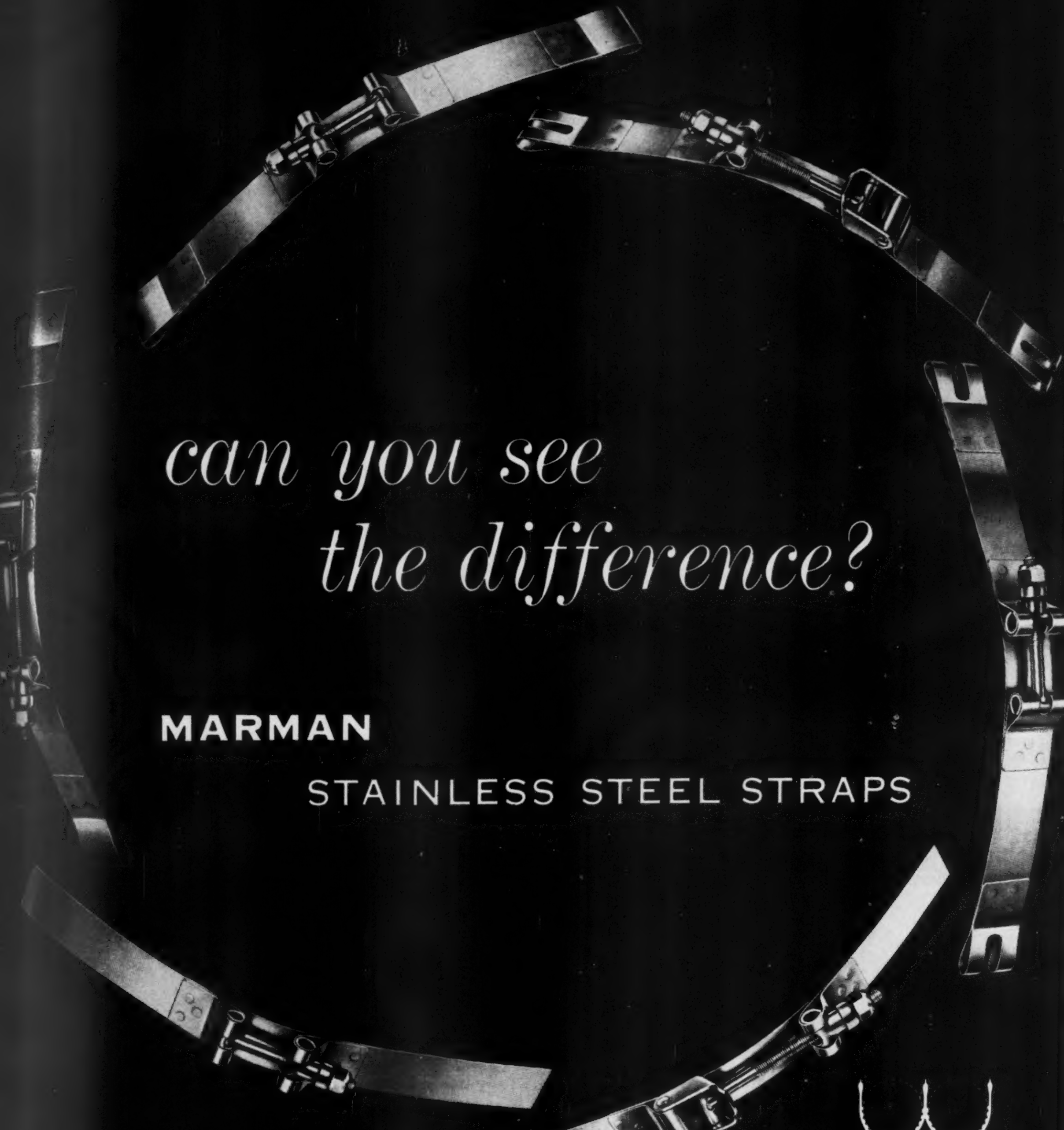

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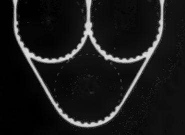

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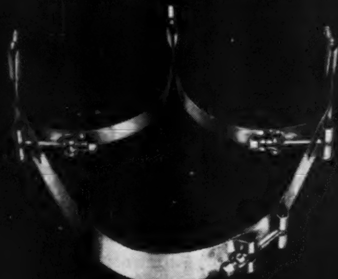

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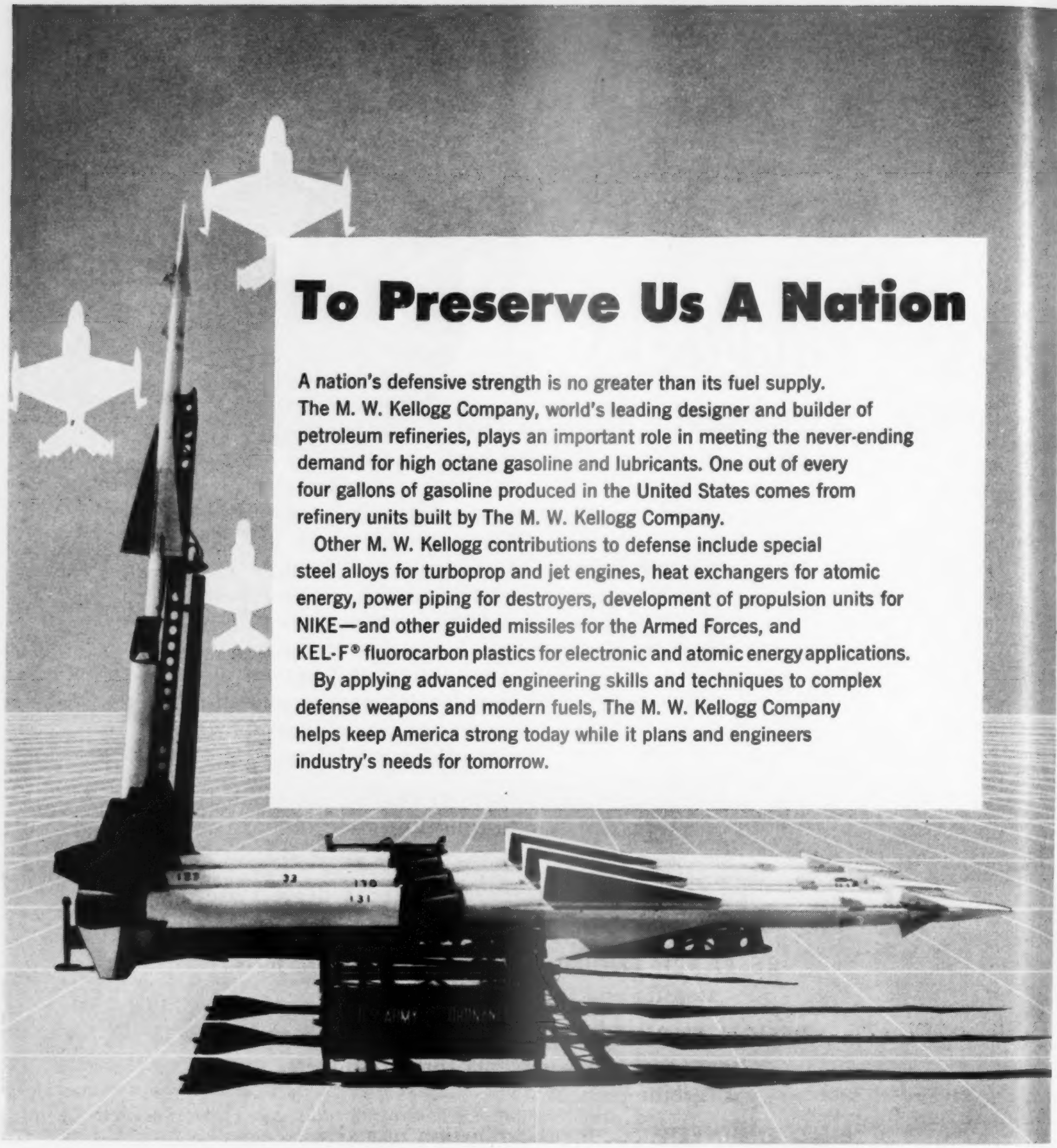
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Editor-in-Chief
MARTIN SUMMERFIELD

Orbital Radio Relays

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While orbital radio relays probably could not compete with microwave radio relay for communication over land, they might be useful in transoceanic communication. Three sorts of repeaters appear to be consistent with microwave art: (a) 100-ft reflecting spheres at an altitude of around 2200 miles; (b) a 100-ft oriented plane mirror in a 24-hr orbit, at an altitude of 22,000 miles; (c) an active repeater in a 24-hr orbit. Cases (a) and (b) require at 10-cm wavelength 250-ft-diam antennas and 100-kw and 50-kw power, respectively; in case (c), using 250-ft antennas on the ground and 10-ft antennas on the repeater, only 100 watts on the ground and 0.03 watt on the repeater would be required; in this case one should probably use smaller antennas on the ground. In cases (b) and (c) the problem of maintaining the correct orientation and position of the repeater is critical; perturbations by the moon and sun might cause the satellite to rock or wander prohibitively.

Introduction

FOLLOWING the announcement last year that the American Telephone and Telegraph Company and the British Post Office have jointly undertaken the construction of a 36-channel two-way submarine telephone cable across the Atlantic at a cost of 35 million dollars, it is natural, at least for a person who is a complete amateur in such matters, to speculate about further developments in transoceanic communication, even into the far future.

Would a channel 30 times as wide, which would accommodate 1080 phone conversations or one television signal, be worth 30 × 35 million dollars; that is, a billion dollars? Will someone spend this much trying to make a broad-band channel to Europe? The idea is of course absurd. At the present, there is no commercial demand which would justify such a channel. By the time there is, surely some technical solution to the problem will be sought which does not involve multiplying the cost of the present cable in proportion to the bandwidth.

It is conceivable that such a solution could come about through further development in the field of cables, but a very difficult step must be taken to multiply the channel capacity by 30 or more. In the meantime, other means for obtaining a broad-band channel to Europe have been considered, including routes largely across land rather than across water.

A route from Labrador or Baffin Island to Greenland, around the coast of Greenland, thence to Iceland and via the Faroe Islands to Scotland traverses much nasty country by land and still leaves gaps of several hundred miles by sea. These gaps might conceivably be spanned by radio, using very high power. Perhaps it may be possible to make undersea television cables which would span gaps of a few hundred miles before such cables can be made to span thousands of miles. Even granting the success of a difficult radio link or a broad-band cable, both terrain and climate make this indirect route difficult and unappealing.

A route from Alaska across the Bering Strait to Siberia, and thence overland to Europe is conceivable, but it is difficult and indirect and it has other disadvantages which need not be mentioned.

Radio relay along a continual chain of planes crossing the Atlantic has been proposed. While this is certainly technically feasible, in good weather at least, it seems strange either as a long-range or a short-range solution.

Another "solution" has been proposed to the problem of transoceanic communication; that is, relaying by means of a satellite revolving about the earth above the atmosphere. Many engineers do not doubt that it will eventually be possible to put a satellite up and into place, nor to supply it with small amounts of power for long periods and to exercise some sort of radio control over it. However, there is no unclassified information in regard to how long it will be before a satellite could be put up or what it might cost to do so, and there may not even be classified information on the subject. Thus, although some aspects of transoceanic communication via a satellite are being considered in this paper, nothing can be said at this point about the over-all feasibility of such communication, which must depend on the feasibility of the satellite itself.

Fortunately, there is a good deal else to be said about the matter. For instance, only *transoceanic* communication has been mentioned, and for a reason. There are at present transcontinental television circuits. The announced cost of the American Telephone and Telegraph Company's transcontinental TD2 microwave system was 40 million dollars. This is only 5 million dollars more than the 35 million for the 36-channel transatlantic cable, and yet the TD2 system provides a number of television channels in both directions, as well as many telephone channels. Perhaps even more important in an overland system, it provides facilities for dropping and adding channels along the route. Without such flexibility, an overland system would be almost useless.

Some types of satellite relay systems would provide communication only between selected points. These would lack the flexibility required for overland service. Further, there is little reason to believe that a satellite relay could compete with present microwave radio relay or coaxial cable in cost. Present facilities are very satisfactory, so that there is little incentive to replace them with some difficult alternative sys-

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[1] Director of Electronics Research.

tem, even if it could do the same job. Thus, satellite radio relay seems attractive only for spanning oceans.

Two different sorts of satellite radio repeaters suggest themselves. One consists of enough spheres in relatively near orbits so that one of them is always in sight at the transmitting and receiving locations. This sphere isotropically scatters the transmitted signal, so one has merely to point the transmitter and receiver antennas at it to complete the path. Another system uses a plane mirror or an active repeater with a 24-hr orbital period, located directly above the equator at a radius of around 26,000 miles or an altitude of about 22,000 miles. Such a satellite would be visible to within 9 deg of the poles; that is, in all inhabited latitudes. If it were not for the perturbations of the orbit by the moon and the sun, it could stay fixed relative to the surface of the earth, and large fixed antennas could be used on earth. However, it appears that perturbation of the orbit would be large enough to necessitate steerable antennas on earth and orientation of the satellite antennas or the reflector by remote control.

Even disregarding problems concerned with the making and placing of the satellites, would such satellite relay systems or any satellite relay system be feasible in other respects? To decide this, two sorts of problems must be considered: problems of microwave communication, and problems lying in the field of celestial mechanics, concerned with the orbit and orientation of a satellite. First to be examined are some of the problems of microwave communication.

Problems of Microwave Communication

Allowable path loss is a dominating consideration in a satellite radio relay system, and the allowable path loss depends on the system of modulation used. Systems of modulation such as binary pulse code modulation, which require small power but large bandwidth, seem particularly suitable. Consider, for instance, an 8-digit binary p-c-m system with a sampling rate of 10 mc and a limiting bandwidth of 5 mc. Such a system allows a ratio of r-m-s quantizing noise to peak-to-peak signal of about 59 db, or a ratio of the power of the maximum-amplitude sine wave which can be transmitted to r-m-s noise of about 50 db. If double-sideband pulses are to be used in connection with such a system, the ideal minimum bandwidth is 40 mc, and an r-f signal-to-noise ratio of around 20 db will be needed if errors are to be kept very infrequent.

Using a 40 r-f band and a 5-mc video band in transmitting high-index f-m would give an f-m gain of about 12 db; adding this to the 20 db r-f noise figure would give an over-all noise figure of around 32 db, which is somewhat worse than that for 8-digit p-c-m. Thus, the following calculations will be based on 8-digit p-c-m.

Further, an r-f receiver noise figure of 6 db will be assumed. This noise figure has been attained in a traveling-wave tube at a wavelength of 10 cm. It may be noted that thermal noise at 20 C (used as a reference in specifying noise figure) is −204 db (db with respect to one watt) for 1 cps bandwidth.

Figures concerning this reference system and the received power required are shown in Table 1.

Table 1

Modulation	8 digit binary p-c-m
Video bandwidth	5 mc
r-f bandwidth	40 mc
r-f signal-to-noise	20 db
r-f noise figure	6 db
r-f received signal	−102 dbw

This figure of −102 dbw may be somewhat optimistic because we have assumed the ideal minimum r-f bandwidth. On the other hand, great care in minimizing the bandwidth would be justified.

Using the power given in Table 1, the allowable path loss vs. transmitter power can now be tabulated, as in Table 2.

Table 2

Transmitter power, watts	Allowable path loss, db
0.01	82
0.1	92
1	102
10	112
100	122
1,000	132
10,000	142
100,000	152
1,000,000	162
10,000,000	172

Matters which govern path loss now need to be explored. In terrestrial microwave systems, fading and atmospheric attenuation are important. In satellite relay communication, no allowance for fading or atmospheric absorption should be necessary. The total mass of the atmosphere, looking through it vertically, is equivalent to about 5 miles of air at sea level. The stratifications which cause changes in path angle, and, hence, fading in long horizontal paths are presumably horizontal and will not much affect transmission near to the vertical. There cannot be a long path through rain when we look up at a steep angle. Thus, all the considerations will be based on free-space transmission.

First the matter of antenna directivity will be considered. For an antenna with a width w and operated at a wavelength λ, the beam width in radians, θ, is roughly

$$\theta = \frac{\lambda}{w} \qquad [2.1]$$

By using this relation, the beam width in miles at a range of 22,000 miles was calculated for several wavelengths and antenna diameters. This information, together with the approximate angular width of the beam in degrees, is given in Table 3. From Table 3, two difficulties can immediately be

Table 3

Wavelength, cm	Beam, width, miles (approx. angular beam width, deg) for antenna diam., ft 1000	100	10
1	0.72 (0.0019)	7.2 (0.019)	72 (0.19)
3	2.2 (0.0056)	22 (0.056)	220 (0.56)
10	7.2 (0.018)	72 (0.19)	720 (1.9)

noted: It is impractical to have a receiving antenna large enough to intercept more than a small fraction of the transmitter power. If large antennas are used, they must be directed very precisely.[3]

If the antenna were to be directed at an essentially fixed object, such as a 24-hr satellite with an orbit unperturbed by sun or moon, then the use of very large fixed antennas built into the earth, steerable over very small angles by moving the feed might be considered. It seems likely that perturbations of the orbit of a "fixed" satellite will be so large as to necessitate a fully steerable antenna. The Jodrell Banks antenna for radio astronomy will have a diameter of 250 ft. It seems reasonable that satisfactory 250-ft antennas could be made for costs compatible with the over-all cost of a satellite project, and henceforward 250 ft will be taken as a maximum antenna diameter. It would, however, be hard to support this as either a maximum or a minimum size.

The path loss depends on other matters than antenna size; it depends on the general sort of repeater that is used. There

are two main types of repeaters: active repeaters, with powered transmitters and receivers, and passive repeaters, i.e., mere reflectors.

Passive Repeaters

Passive repeaters are very attractive in many ways. They would require no maintenance and they would be almost immune to meteor damage. It will be shown that some kinds might require remote control devices for orientation, but these could be simple.

Isotropic Reflectors

One type of passive repeater which will be considered is a sphere, which acts as an isotropic reflector and scatters the intercepted power equally in all directions. Such a repeater is of use between any two locations in sight of it.

If A_T is the area of a transmitting antenna and A_R is the area of a receiving antenna,[2] the ratio of power received to power transmitted, P_R/P_T, is

$$\frac{P_R}{P_T} = \frac{A_T\,A_R}{\lambda^2 d^2} \qquad [2.2]$$

Here λ is the wavelength and d is the distance between the transmitting antenna and the receiving antenna.

Suppose that the transmitting antenna has an area A_1 and the sphere which "receives" the power at a distance d a cross-sectional area A_2. Suppose that the sphere scatters the power uniformly over a solid angle of 4π radians and that the power finally received falls on an antenna of one A_1 at a distance d. Then the over-all ratio of power received to power transmitted $(P_R/P_T)_2$ is

$$\left.\begin{aligned}\left(\frac{P_R}{P_T}\right)_2 &= \left(\frac{A_1A_2}{\lambda^2d^2}\right)\left(\frac{A_1}{4\pi d^2}\right)\\ \left(\frac{P_R}{P_T}\right)_2 &= \frac{A_1^2A_2}{4\pi\lambda^2d^4}\end{aligned}\right\} \qquad [2.3]$$

Circular transmitting and receiving antennas with diameters of 250 ft, a sphere with a diameter of 1000 ft, and a wavelength of 10 cm are considered. For a range of 22,000 miles the path loss will be 171 db. Referring to Table 2, it is seen that this would require a power of around 10 megawatts. Even allowing for the fact that a transmitter for binary p-c-m is on only half the time on the average, this seems a ridiculously high figure.

Going to a wavelength of 3 cm would cut the power requirement down by a factor of 10, but the power required still seems much too high.

The use of a number of spheres at some lower altitude might also be examined. There will certainly be a need to transmit over a total path length of thousands of miles. If, for example, a distance to the sphere of 2200 miles is taken, instead of 22,000 miles, then from Equation [2.3] is it seen that this would decrease the path loss by only 40 db, making the power requirement 1 kilowatt. However, a multiplicity of spheres is now needed, and perhaps a diameter of 1000 ft is unreasonable (even for one sphere, perhaps). Calling the diameter of the spheres to 100 ft would up the power by 20 db, calling for 10 kw at 10-cm wavelength.

Plane Mirror

Suppose that a slightly concave mirror is used as a passive repeater. This could act as a perfectly focused transmitting and receiving antenna. If it is assumed, as it has been, that the transmitting antenna and the receiving antenna are equidistant from the mirror and 22,000 miles away from it, then the radius of curvature of the mirror should be 22,000 miles or 1.16×10^8 ft. If the diameter were 1000 ft, the concavity or depth of the mirror would be 2.16×10^{-4} ft or 2.5 mils. As this is small compared with the wavelength, the mirror can just as well be flat. Thus, it could act as a relay from any point in sight of its surface to a particular corresponding point.

Let A_2 be the area of the mirror. To get the over-all power ratio (P_R/P_T), Equation [2.2] is used twice: for going to the mirror, and back. We obtain

$$\left(\frac{P_R}{P_T}\right)_2 = \frac{A_1^2A_2^2}{\lambda^4d^4} \qquad [2.4]$$

Again considering a 10-cm wave-length, 250-ft circular antenna and a 100-ft circular mirror, a path loss of $(P_R/P_T)_2 =$ 139 db is computed. According to Table 2, this would allow operation with a power of 50,000 watts.

In using a plane mirror there is a serious problem of satellite position and orientation. If the repeater moves x miles out of the position, the reflected beam moves $2x$ miles on the ground; if the repeater swings through an angle θ the reflected beam swings through an angle 2θ. From Equations [2.1] and [2.4] it is seen that changing the wavelength and the mirror diameter so as to keep the path loss constant does not affect the width of the returned beam. The requirements on orientation can be relaxed only by reducing the mirror diameter in wave lengths.

With a 100-ft mirror and a 10-cm wavelength, the beam is only 0.19 deg wide, which means that the mirror must be oriented to less than half of this angle, and the beam is only 72 miles wide at the surface of the earth.

A Corner Reflector

Suppose there is a corner reflector in a 22,000-mile equatorial orbit. Wherever this could be seen, it could be used to broadcast in the vicinity of the transmitter, for it will send what energy it receives back toward the transmitter. For zero wave length, radiation would fall over an area twice as great as that of the corner reflector. Actually, the area will be governed by the wavelength as well as by the size of the reflector as show in Table 2, and Equation [2.4] will apply.

It may be seen from Table 3 that, to get a reasonable coverage, only a rather small corner reflector can be used—say, 10-ft diam at a wavelength of 10 cm—and only a small receiving antenna, say, 4-ft-diam. Assuming transmitting antenna 250 ft in diam, the path loss turns out to about 211 db, which is much too high.

Active Repeaters

The big advantage of an active repeater is that the size and directivity can be relatively small. Thus, the orientation need not be as accurate as in the case of a plane reflector. It would seem desirable to make the repeater as small and as low-powered as possible, and hence one should perhaps use as large a receiving antenna on earth as seems reasonable. Thus, an antenna diameter of 250 ft will be assumed, as in the case of passive repeaters. A repeater antenna 10 ft in diam will be assumed. At a wavelength of 10 cm, the computed path loss computed by means of Equation [2.2] is 87 db.

Referring to Table 1, it is seen that this would require a transmitter power of only 0.03 watt or 30 milliwatts.

What about the link from earth to the satellite? Assume that a 250-ft transmitting antenna, a 10-ft receiving antenna, and transmitter power of 100 watts are used. Then the noise figure of the satellite receiver could be over 40 db, and the gain required would be only 52 db.

With these requirements, a single, low-voltage, low-performance traveling-wave tube should be quite adequate. Such a tube could be designed for very low cathode current density, and hence for long life. It could be operated by solar

[2] Neither here nor later is any distinction made between geometrical area and effective area of antennas. This will make a difference of a few db only, an amount negligible among other uncertainties.

batteries if some sort of storage could be provided. A 30-milliwatt traveling-wave tube, exclusive of power supplies could weigh 2 lb or less. Its power consumption, chiefly cathode power, could be 5 watts or less.

It may be noted from Table 3 that the orientation of the repeater could vary perhaps $\pm 1/2°$ and the location perhaps ± 200 miles.

3 Some Mechanical and Astronomical Problems

While no consideration will be given to the actual problem of getting a satellite into position, some consideration should be given to mechanical and astronomical problems before any comparison is made between the various systems discussed in the preceding section.

Weight

There now follows a very rough examination of what the weight of metallic spheres and mirrors might be.

Aluminum weighs 168.5 lb/ft^3. The area of a 100-ft circle is 7850 ft^2 and that of a 100-ft sphere is 4 times this. If the foil were 1 mil thick, the weight of the 100-ft mirror would be 110 lb and that of a 100-ft sphere would be 440 lb. The weight of a 1000-ft sphere would be 100 times as much, or 44,000 lb.

The mirror would have to be stretched on a frame which would weigh several hundred pounds.

To keep the sphere spherical, initially one could inflate it gently. Thereafter, loss of pressure because of meteor puncture would be expected. The spherical shape could be maintained either by straining the skin in the initial inflation, or by fastening to the sphere a beta emitter, so that the sphere would become positively charged and maintain its shape by means of electrostatic repulsion.

As opposed to the sphere, the mirror might be made out of mesh (e.g., tungsten mesh), with openings small compared with a wavelength.

Orbit

A sphere need only be put into the proper orbit. For a 24-hr orbit, intended to keep the sphere fixed in the sky, this would have to be done with considerable accuracy. An error of altitude of 1 ft would cause a drift out of position of 0.65 mile/year. If a drift of 10,000 miles (about 30 deg) in 50 years is allowed, the altitude would have to be accurate to about 300 ft. It is possible to measure the altitude much more accurately than this by means of radar, if only the astronomers can tell accurately what altitude the satellite should be put at.

There may, then, be envisioned an unmanned rocket maneuvered into position over a period of time by remote control guided by radar. Either the rocket could itself become the desired satellite by sprouting antennas or a reflector, or it could blow up a sphere and release it.

The subsequent orbit of the satellite is a problem for the astronomers. It would be very interesting to know how far about the sky a 24-ft "fixed" satellite would wander under the influence of the moon and the sun.

Orientation

A sphere need not be oriented in its orbit, but a satellite bearing a passive reflector or antennas would have to maintain a fixed orientation with respect to the surface of the earth.

It is not entirely out of the question to maintain such orientation automatically without expenditure of power. Consider a long beam revolving in an orbit. If it is in a radial orientation and is rotated slightly, there will be a restoring force tending to return it to radial orientation. The genesis of this force is easy to see. In the radial orientation the gravitational force on the outer portions is less than that on the inner portions, while the centrifugal force on the outer portions is greater than that on the inner portions. The beam is under tension. If the beam is rotated so as to bring the outer portions in, there is a couple acting against this rotation.

If the beam were forced to be normal to the radial direction there would be a couple tending to align it in the plane of the equator because the gravitation forces and the centrifugal forces do not act toward the same center. For a given angular displacement, this couple is less than that tending to align the beam radially.

A long, pointed equilateral triangle would tend to orient itself in the plane of the equator with the pointed end pointing radially in or out. More generally, of the principal axes of inertia, that about which the moment of inertia is greatest would tend to align itself parallel to the earth's axis, and that about which the moment of inertia is least would tend to align itself radially.

If the body were released in any different orientation it would oscillate forever about this preferred orientation unless damping were provided. The damping could be in the form of viscous liquid in a partly filled tube or container, or, preferably, unbalanced mechanical devices resonant at the frequencies of the natural oscillations of the body about its principal axes.

The natural period of oscillation can be calculated in a straightforward manner. For example, a simple body consisting of two equal masses connected with a rigid rod would tend to orient itself with the rod directed toward the center of the earth, and if slightly displaced in the equatorial plane it will oscillate with a period τ:

$$\tau = 2\pi \left(\frac{r_0}{3g_0}\right)^{1/2} \cdot \left(\frac{r}{r_0}\right)^{3/2} = 0.84 \left(\frac{r}{r_0}\right)^{3/2} \text{ hr}$$

where g_0 is the standard gravitational acceleration, r_0 is the radius of the earth, and r is the radial distance to the body. At 22,000 miles, the period would be 11 hr.

By fastening a mirror to a properly proportioned structure provided with damping, the mirror should automatically assume a fixed orientation with respect to the surface of the earth.

Perturbations by the moon both in the oribit and in the orientation of the repeaters would certainly rule out an automatic orientation. However, there might still be considered a remotely operated radio-controlled device which could correct orientation by shifting weights. Such a device could use transistors, very small motors, and perhaps solar batteries for power. The operation would be slow and intermittent. The control could be through very high-power pulsed signals, so as to call for a small low-directivity antenna on the satellite. The total power required might be less than for a relay receiver and transmitter.

4 Summary and Discussion

A number of problems in connection with satellite repeaters have been discussed in the previous sections. Endless variations and refinements could be made in assumptions. Perhaps frequency of operation and the antenna size should be considerably different from what has been assumed. However, the feasibility and cost of placing various sorts of satellites, which has not been, nor could be, discussed, would certainly strongly influence the nature and the size of satellite one might use.

Thus, the best that can be done is an attempt to state some sort of conclusions concerning the sorts of systems which have been described.

To aid in this discussion, some of the data arrived at earlier have been summarized in Table 4. All of these are for a 5-mc video channel provided by an 8-digit binary pulse code modulation system, as described in Table 1, and a wavelength

Table 4

Path length, miles	Repeater description	Power on earth	Repeater output	Orientation must be better than
22,000	1000-ft sphere	10 megawatts	0	No orientation
2,200	100-ft sphere	100 kw	0	No orientation
22,000	100-ft mirror	50 kw	0	±18 miles ±0.047 degree
22,000	10-ft antennas	100 watts	30 mw	±360 miles ±0.95 degree

of 10 cm. The diameter of the antennas on earth is assumed to be 250 ft.

The great advantages of the passive repeaters over active repeaters are potential channel capacity and flexibility. Once in place, passive repeaters could be used to provide an almost unlimited number of two-way channels between various points at various wavelengths. They would also allow for modifications and improvements in the ground equipment without changes in the repeater.

Spheres, which reflect isotropically, are the most flexible of passive repeaters, because they allow transmission between any two points in sight of them. Moreover, with spheres there is no problem of the angular orientation of the repeaters.

For a 24-hr "fixed" repeater and a 1000-ft sphere, the power required is 10 megawatts, and this seems excessive. However, suppose 10 spheres, each 100 ft in diameter, circled the earth above the equator at a fairly low altitude. At low latitudes, one or more would always be in sight. The path length would be only about a tenth that for the 24-hr orbit, and the power required would be around 100 kw, which seems quite feasible.

A plane mirror returns much more power than does a sphere of the same diameter. A 100-ft mirror at an altitude of 22,000 miles would call for a transmitter power of about 50 kw, which again is by no means unreasonable.

The great problem in connection with a plane mirror is that of position and orientation. If it were not for the perturbation caused by the moon and sun, the position and orientation of the mirror could be preserved automatically by a proper disposition of masses attached to the mirror and by the use of damping.

However, as perturbations of position and orientation will be too large to be tolerated, the orientation of the mirror would have to be adjusted by moving masses through radio control. The power required would be small, perhaps less than that required for an active repeater. The advantage of channel capacity would be preserved.

The plane mirror suffers a considerable limitation compared with the sphere, however. If it really hung fixed in the sky, it would provide communication between any point in sight of its face and another particular corresponding point. However, because perturbation by the sun and moon will cause it to wander about in the sky so that the orientation of the mirror must be adjusted to maintain a path between two particular points, a plane mirror can actually be used only to provide channels (and a large number of channels on different frequencies) between two particular points.

The disadvantage of passive repeaters is the great path loss, so that even assuming antennas of a difficult if not prohibitive diameter and accuracy, the power required is large, although probably attainable.

The attractive feature of an active repeater is the small power required and the small antennas needed at the repeater, as well as the small power required at the ground. Indeed, an actual design for an active repeater would probably call for smaller antennas on earth, perhaps for larger antennas on the statellite, and probably for higher powers on both earth and satellite. Because the antennas on the satellite would have a comparatively small directivity, and because for a given angular or positional shift the beam from a radiator shifts only half as far as the beam from a reflector, the orientation problem is considerably easier in the case of an active repeater than in the casé of a plane reflector. However, there still is an orientation problem, in contrast to the case of a sphere used as a passive repeater.

The chief disadvantage of the active repeater, aside from disadvantages of power supply and life, is that it provides only the number and sort of channels that are built into it. Once it is in place, its channel capacity cannot be substantially increased by anything done on the ground, although some gain might be made by an increase in transmitter power and receiver sensitivity and by a modification of the nature of the signal.

In conclusion, it can be said that, disregarding the feasibility of constructing and placing satellites, it seems that it might be possible to achieve broad-band transoceanic communication using satellite repeaters with any one of three general types of repeater: spheres at low altitudes, or a plane reflector or an active repeater in a 24-hr orbit (at an altitude of around 22,000 miles).

At this point, some information from astronomers about orbits and from rocket men about constructing and placing satellites would be decidedly welcome.

Background

The basis for the microwave calculations in this paper will all be found in the references below (1–4). A fine over-all treatment of microwave repeaters is available (5). The reader may also be interested in the current status of the microwave tube art (6).

It is interesting to note that the problem of radio links to the planets has been treated by Richey as early as 1938 (7) and in considerable detail by J. J. Coupling in 1952 (8).

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The Determination of Transient Temperatures and Heat Transfer at a Gas-Metal Interface Applied to a 40-mm Gun Barrel

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The problem of measuring very rapidly changing temperature and heat transfer at a gas-solid interface is becoming of increasing importance. This paper presents a method of doing this under the conditions of unidirectional heat flow in a semi-infinite solid. Temperatures are measured very near the metal surface by means of a special type of thermocouple. Equations are derived in which resulting thermocouple measurements are used to calculate the heat transfer through the surface. The method is illustrated by application to a 40-mm gun barrel. Experimental temperature records from four thermocouples installed along the barrel are shown. The ballistic heat transfer at these locations is determined from these records. The experimental temperature curves are also compared with theoretical results.

Nomenclature

- c_p = specific heat at constant pressure, cal/gm °C
- k = thermal conductivity, cal/cm² sec °C/cm
- $q(t)$ = heat rate, cal/cm² sec
- $Q(t)$ = heat transferred in cal/cm² up to time, t
- T = temperature, °C
- T_i = interface temperature immediately after contact of two semi-infinite bodies, °C
- t = time, sec
- x = distance measured into gun barrel normal to bore surface, cm
- α = thermal diffusivity, cm²/sec
- λ, a = variables of integration, sec
- μ = variable of integration = $x/2\sqrt{\alpha(t-\lambda)}$
- $\phi(t)$ = function defining the variation of surface temperature with respect to time

Introduction

VARIOUS examples of increased attention being given to transient heat transfer may be cited. Among these are rockets, jet engines, automatic control instrumentation, and gun barrels. It was with this last item that the work[2] described in this paper was specifically concerned. It was desired to measure the heat transfer to the barrel from the powder gases up to the time of projectile exit from the muzzle (ballistic heat transfer) as well as the total heat transfer to the barrel. Previous investigations had measured only total heat transfer either by using the gun barrel as a calorimeter or by assuming the heat input to be instantaneous and calculating the magnitude from outer surface or embedded thermocouple measurements.

Interest in bore-surface temperature measurements (1)[3] led to investigation of the determination of heat transfer from them. It was found that under the conventional assumptions of unidirectional heat flow in a semi-infinite solid and constant average thermal properties, ballistic or total heat transfer could be determined from a record of the temperature or at very close to the bore surface. This involved the fabrication of a special type of thermocouple and recording equipment. The technique used will be described following presentation of the theoretical considerations involved.

Calculation of Heat-Transfer From Surface Temperature Measurements

Assuming that the heat conduction in a gun barrel parallel to the surface can be neglected and that the barrel can be treated as a semi-infinite solid, the temperature distribution as a function of time, t, and distance from the bore surface, x, is given by

$$T(x, t) = \frac{x}{2\sqrt{\pi\alpha_g}}\int_0^t \phi(\lambda)\frac{e^{\frac{-x^2}{4\alpha_g(t-\lambda)}}}{(t-\lambda)^{3/2}}d\lambda \quad \ldots\ldots [1]$$

when the variation of the surface temperature with time, $\phi(t)$, is known. To determine the heat-transfer rate through the surface, it is necessary to know the temperature gradient there and the value of the thermal conductivity, k_g. If an average value of k_g is used, the heat rate as a function of time in cal/cm² sec is then given by

$$q(0, t) = -k_g\frac{\partial T(0, t)}{\partial x} \quad \ldots\ldots [2]$$

To obtain the temperature gradient, $(\partial T(x, t)/\partial x)$, it is convenient to change the form of Equation [1] by substitution of the variable

$$\mu = \frac{x}{2\sqrt{\alpha_g(t-\lambda)}} \qquad \text{Then} \quad (t-\lambda) = \frac{x^2}{4\alpha_g\mu^2}$$

and

$$T(x, t) = \frac{2}{\sqrt{\pi}}\int_{x/2\sqrt{\alpha_g t}}^{\infty}\phi\left(t - \frac{x^2}{4\alpha_g\mu^2}\right)e^{-\mu^2}\,d\mu \quad \ldots [3]$$

Partial differentiation with respect to x and return to original variables gives

$$\frac{\partial T(x, t)}{\partial x} = \frac{-1}{\sqrt{\pi\alpha_g}}\int_0^t\frac{d\phi(\lambda)}{d\lambda}\frac{e^{\frac{-x^2}{4\alpha_g(t-\lambda)}}}{(t-\lambda)^{1/2}}d\lambda - \frac{e^{\frac{-x^2}{4\alpha_g t}}}{\sqrt{\pi\alpha_g t}}\phi(0) \quad \ldots [4]$$

and for the heat rate

$$q(x, t) = \frac{k_g}{\sqrt{\pi\alpha_g}}\int_0^t\frac{d\phi(\lambda)}{d\lambda}\frac{e^{\frac{-x^2}{4\alpha_g(t-\lambda)}}}{(t-\lambda)^{1/2}}d\lambda + k_g\frac{e^{\frac{-x^2}{4\alpha_g t}}}{\sqrt{\pi\alpha_g t}}\phi(0) \quad \ldots [5]$$

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[2] The work described in this paper was performed for the Bureau of Ordnance of the U. S. Navy Department under Task II of Contract NOrd 12102. Their interest in and approval for its presentation are gratefully acknowledged.

[3] Numbers in parentheses indicate References at end of paper.

It is necessary to consider this equation both at the surface, $x = 0$, and at a very short distance below the surface where the actual temperature variation is recorded. Taking the surface first, it will be observed that some simplification results from the exponential term becoming 1. The time derivative of the surface-temperature curve required for the integrand in the first term would, in general, have to be deterined graphically from an experimental temperature curve. Evaluation of the second term rests on defining the value of $\phi(0)$. This can be done quite plausibly in the following way. Consider a small area of the gun barrel which has just suddenly been exposed to hot propellant gases following the projectile. Because the instantaneous temperature effects are known to be confined to short distances from the gas-barrel interface in either the gas or barrel, it is logical to expect that the physical situation occurring here would be similar to that of bringing together two semi-infinite solids of different temperatures. The solution for the temperature of the interface in such a situation is given by (3)

$$T_i = \frac{k_p T_p/\sqrt{\alpha_p} + k_g T_g/\sqrt{\alpha_g}}{k_p/\sqrt{\alpha_p} + k_g/\sqrt{\alpha_g}} \quad \ldots\ldots\ldots\ldots [6]$$

and the heat rate by

$$q_i = \frac{k_g(T_i - T_g)}{\sqrt{\pi\alpha_g t}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [7]$$

If the initial gun temperature, T_g, is taken as the datum, it will be noted that this is similar in form to the second term of Equation [5] when $x = 0$. Comparison of the two indicates the specification of $\phi(0)$ at the surface as T_i. This is further justified by the consideration that in the absence of subsequent convection heat transfer by the propellant gases, the interface temperature would remain constant, $(d\phi(\lambda)/d\lambda) = 0$, and Equation [5] would reduce to Equation [7].

Turning now to a consideration of Equation [5] at a very short distance below the surface (approximately 0.0002 in.), the procedure used is to consider again $x = 0$ at that location. Again the exponential terms are eliminated and, in addition, the second term goes to zero. The reason for this is that only at the actual solid-gas interface immediately following contact is the solid temperature different from the datum, T_g. Evaluation of the first term gives the heat transfer across the plane at which the temperature is measured. Extrapolation of the measured temperature variation to the actual surface by means of a Schmidt plot can be made (1, 3). This would permit approximate correction of the heat-transfer rate below the surface to that at the surface. If it is desired to determine only the heat transferred up to any time, t, however, it is not necessary to do this as a simpler method can be used. This is to graphically determine the heat transfer across the plane below the surface from a heat-rate curve and add to that the heat stored in the layer between this plane and the surface at the given time, t. The equation to be used for heat-rate calculations is therefore

$$q(t) = \frac{k_g}{\sqrt{\pi\alpha_g}}\int_0^t \frac{d\phi(\lambda)}{d\lambda}\frac{d\lambda}{(t-\lambda)^{1/2}} \quad \ldots\ldots\ldots\ldots [8]$$

The procedure just outlined for evaluating the heat transfer to a semi-infinite solid up to any time, t, involves the graphical differentiation of an experimental temperature curve. Under some circumstances, this is desirable in that a curve of heat rate versus time is obtained in the process. It is possible, however, to eliminate this step by integration of the heat-rate Equation [5]. That is,

$$Q(t) = \int_0^t q(\lambda)\,d\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots [9]$$

To perform this integration, it is again convenient to introduce the variable $\mu = x/2\sqrt{\alpha_g(t-\lambda)}$ in Equation [5]. When this is done and $a = t$ is used as the variable of integration, Equation [9] becomes

$$Q(t) = \frac{k_g}{\sqrt{\pi}}\int_0^t\int_{x/2\sqrt{\alpha_g t}}^{\infty} \frac{d\phi\left(a - \dfrac{x^2}{4\alpha_g\mu^2}\right)}{d\left(a - \dfrac{x^2}{4\alpha_g\mu^2}\right)}\frac{xe^{-\mu^2}}{\alpha_g\mu^2}\,d\mu\,da + \frac{k_g}{\sqrt{\pi}}\int_0^t \frac{\phi(0)e^{\frac{-x^2}{4\alpha_g a}}}{\sqrt{\alpha_g a}}\,da \quad \ldots\ldots [10]$$

If the order of integration in the first term is reversed, this equation takes the following form:

$$Q(t) = \frac{k_g}{\sqrt{\pi}}\int_{x/2\sqrt{\alpha_g t}}^{\infty}\frac{xe^{-\mu^2}}{\alpha_g\mu^2}\int_{x/4\alpha_g\mu^2}^{t}\frac{d\phi\left(a - \dfrac{x^3}{4\alpha_g\mu^2}\right)}{d\left(a - \dfrac{x^2}{4\alpha_g\mu^2}\right)} \times da\,d\mu + \underline{k_g\phi(0)}\int_0^t \frac{e^{\frac{-x^2}{4\alpha_g a}}}{\sqrt{\alpha_g a}}\,da \quad \ldots\ldots [11]$$

It is now possible to perform the integration with respect to a, which gives

$$Q(t) = \frac{k_g}{\sqrt{\pi}}\int_{x/2\sqrt{\alpha_g t}}^{\infty}\phi\left(t - \frac{x^2}{4\alpha_g\mu^2}\right)\frac{xe^{-\mu^2}}{\alpha_g\mu^2}\,d\mu \quad \ldots\ldots [12]$$

The second term is cancelled in this step. Substituting now in terms of the original variables and reducing to the surface where $x = 0$, results in a final equation

$$Q(t) = \frac{k_g}{\sqrt{\pi\alpha_g}}\int_0^t \frac{\phi(\lambda)}{(t-\lambda)^{1/2}}\,d\lambda \quad \ldots\ldots\ldots\ldots [13]$$

Experimental Equipment and Test Results

Bore-Surface Temperature Thermocouples

A method for measuring gun bore-surface temperature variation during firing, as developed in Germany around 1940, is described by Hackemann (1). This involved the fabrication of a special type of thermocouple and associated recording equipment. A typical installation is shown schematically in Fig. 1. A thermocouple unit is constructed from a gun-steel

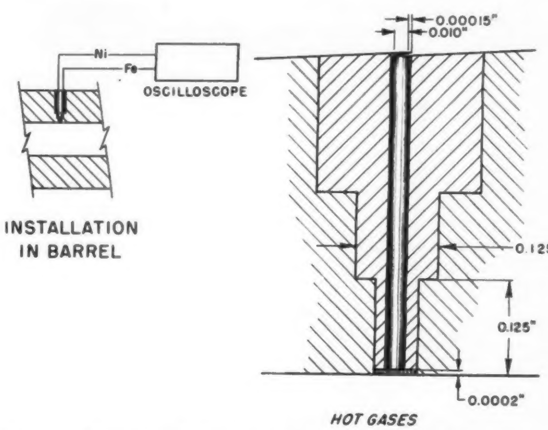

Fig. 1 Thermocouple for measuring gun bore-surface temperature

blank and an oxidized nickel wire using the following procedure: First, a hole 0.010 in. in diam is drilled in the tip, and a hole 0.032 in. in diam is drilled through the rest of the blank. After the hole in the tip is carefully polished, an oxidized

nickel wire is inserted and the tip is plastically deformed around the wire with an upsetting tool. Use of a relatively small-diameter wire is dictated by the high pressures to which the unit will be exposed. Oxidation of the wire can be successfully accomplished by electrical heating in a controlled atmosphere (4). Heating in a gas flame for about an hour with the wire around 800 F was found, however, to be a better procedure. Not only are the oxide qualities superior, but the wire is much less likely to break with subsequent handling.

After the tip is deformed around the oxidized nickel wire, the end surface of the tip is ground and polished. The surface is cleaned electrolytically before plating to remove any loose particles of metal. Fig. 2 shows the end surface of a steel unit

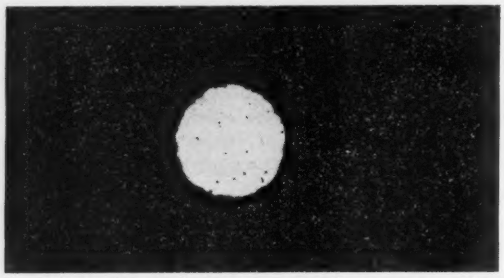

Fig. 2 Photomicrograph of thermocouple tip after polishing (nital etch, magnification 100 ×)

thus prepared. A 0.0004-in. thick nickel coating is plated on this face and then ground down to approximately 0.0002 in. A solution of commercially pure nickel sulfate, nickel chloride, and boric acid maintained at 55 C with a pH around 4.5 is used. A check on the intended structure and a measure of the final nickel-layer thickness are provided by a photomicrograph of a 45-deg section as shown in Fig. 3. Since determination of the final thickness of the layer is difficult, cross-sectioning seems to be the most reliable technique. Control of plating and final polishing time, however, has been found to yield satisfactory results.

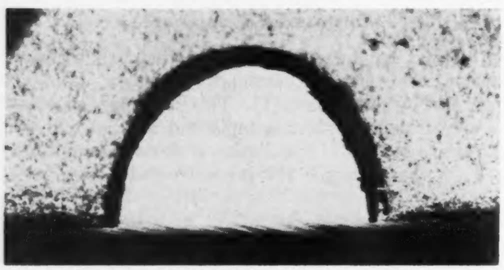

Fig. 3 Photomicrograph of 45° section through thermocouple tip (magnification 250 ×)

A calibration curve for the units was obtained by comparison to a Pt-PtRh thermocouple in a furnace. The response is not linear but is approximately 2.3 mv per 100 C. In so far as has been determined, the oxide is not electrically insulating when held at temperatures above 500 C. The length of time it is exposed to temperatures above this in a gun barrel is, however, very short and breakdown does not occur.

40-mm Gun Barrel Installation and Test Results

The installation of four of these thermocouple units and a piezo gage in a 40-mm gun barrel is shown schematically in Fig. 4. The gun is operated remotely by means of a solenoid-driven air cylinder. A microswitch triggers the instrumentation circuit just after the breech block closes.

Temperature and combustion-chamber pressure records obtained during the firing of standard rounds (890 gm projectile with a 293 gm charge of SPDN 7184 powder) are shown in Fig. 5. These traces were not all recorded during the same round, but results were found to be of such consistency that the records can be considered as representative of any one round.

The maximum pressure as indicated by a DuPont piezoelectric gage was 46,000 psi. Performance of the thermocouples was quite satisfactory in that no recession of the nickel wire occurred. A life of ten rounds is quite possible if care is exercised in proper location of the unit with respect to the bore surface. If the unit is positioned too far from the surface there is a tendency for metal from the projectile engraving band to fill the resulting cavity. A recess of about 0.002 in. appears satisfactory.

Calculation of Heat Transfer

The composite plot of pressure and temperatures shown in Fig. 6 has been prepared from oscillograph records of single firings of 40-mm service rounds. Beginning of combustion-chamber pressure rise has been arbitrarily selected as the point of zero time. The projectile leaves the muzzle approximately 4.25 millisec later with a velocity of 2700 fps.

It is interesting to note in Fig. 6 that the combustion-chamber pressure has reached its peak and dropped off considerably by the time the surface temperature at the first thermocouple has reached its maximum. A rather large decrease in the maximum temperature from the No. 1 to the No. 2 position is also noted. These results are evidence of complete burning of the powder early during projectile travel, followed by rapid cooling of the gases during expansion.

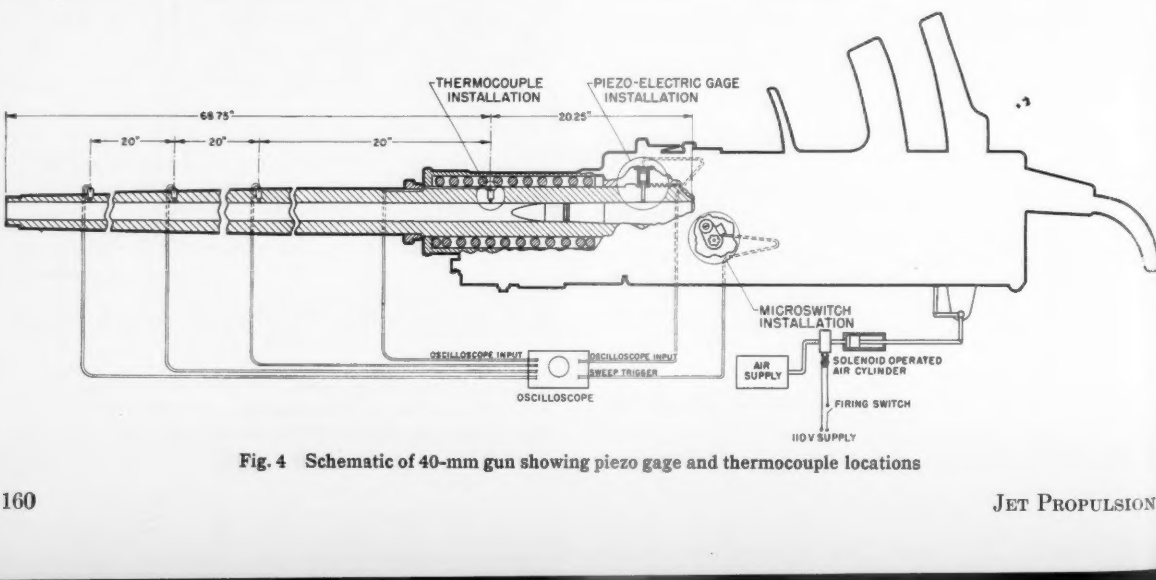

Fig. 4 Schematic of 40-mm gun showing piezo gage and thermocouple locations

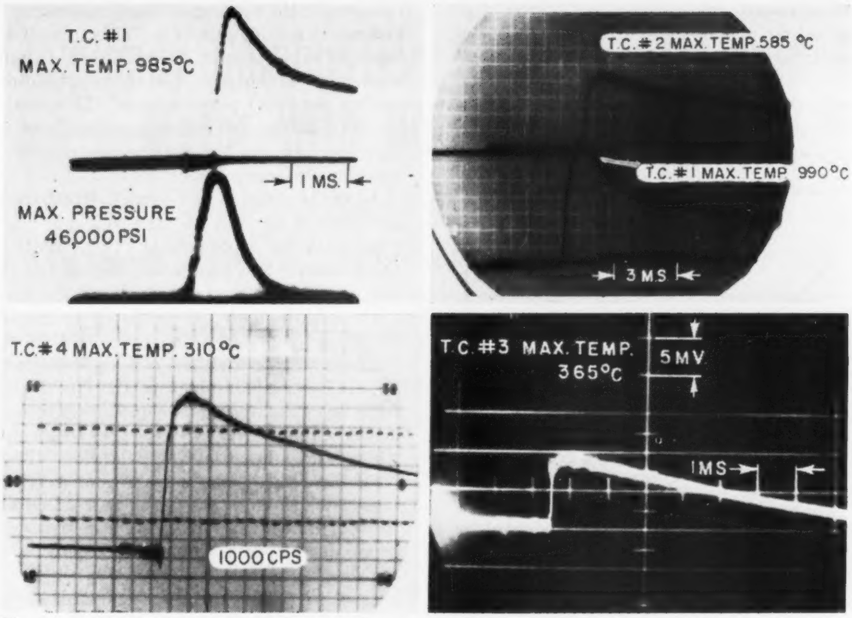

Fig. 5 Oscillograph records of bore-surface temperatures and combustion chamber pressure during single firings of standard rounds in a 40-mm gun

The curves of heat rate vs. time shown in Fig. 7 have been calculated by graphical differentiation of the temperature curves in Fig. 6 and use of Equation [8]. (Average values of the thermal conductivity and diffusivity used were 0.11 cal/cm² sec °C/cm and 0.096 cm²/sec, respectively.) As pointed out previously, this equation actually applies to the plane 0.0002 in. below the bore surface. Correction to surface values was not made since the accuracy is not considered better than 10% (based primarily on preciseness with which oscillograph records can be transcribed and possible error in the values used for the thermal properties). Calculations were carried out to just beyond projectile exit time to permit evaluation of the ballistic heat transfer. Attention is called to the fact that, if local gas-stream temperature variation were known, the variation of the local heat-transfer coefficient with time could be determined from these curves. It is of interest to note that the maximum heat rate shown in Fig. 7 is approximately 185,000,000 Btu/hr ft.² The heat transfer coefficient for this condition is estimated to be of the order of 50,000 Btu/hr ft² °F.

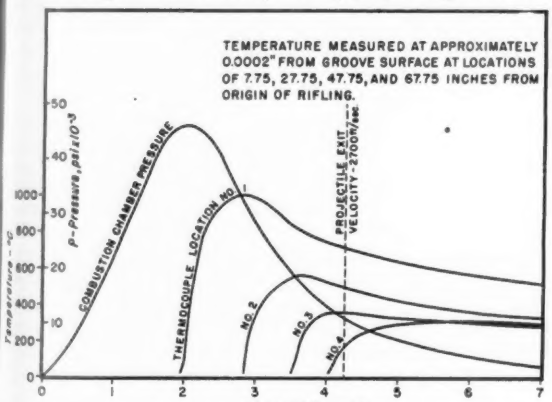

Fig. 6 Temperature and pressure records in a 40-mm antiaircraft gun barrel during firing of a standard service round

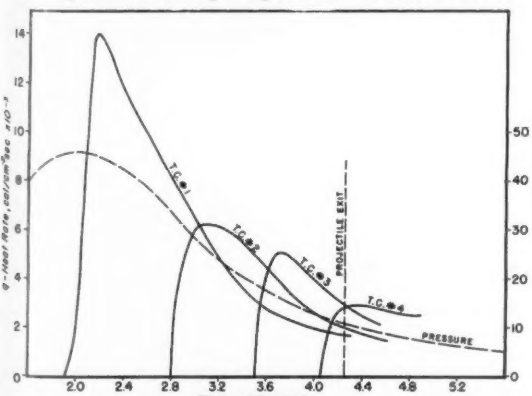

Fig. 7 Heat rate vs. time at four thermocouple locations in the 40-mm barrel

The heat transferred to the barrel at the respective thermocouple locations up to a specified time, such as projectile exit, can be determined by graphical integration of the areas under the curves of Fig. 7 up to the given time. A quicker and more accurate means of obtaining these values is by use of Equation [13], which provides a curve of heat transfer at a given location as a function of time. Such curves for the four thermocouple locations are shown in Fig. 8. No correction for the heat stored in the 0.0002-in. layer between the surface and

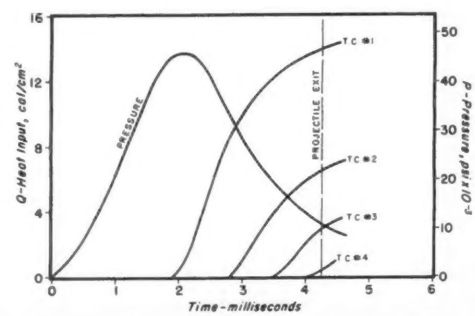

Fig. 8 Heat transfer vs. time at four thermocouple locations in the 40-mm barrel

point of temperature measurement has been made, since it is less than 5 per cent and the experimental error and variation from round to round are estimated to be of the order of 10–15 per cent.

The distribution of ballistic heat transfer along the barrel as determined from the values of the curves in Fig. 8 at the time of projectile exit is shown in Fig. 9. The extrapolation of

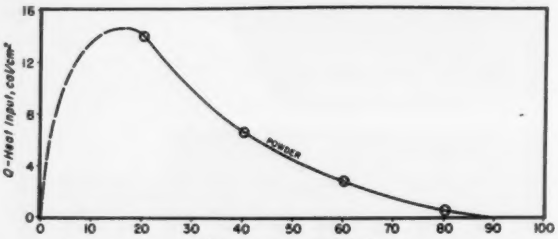

Fig. 9 Ballistic heat transfer distribution in the 40-mm barrel

the curve to the origin at the left is dashed as it involved the problem of how to treat the section of the barrel covered by the shell case. Since this region is not of particular concern, no further consideration has been given to it. An average value of heat transfer in cal/cm² has been determined from Fig. 9. When multiplied by the entire bore surface area, it gives a value of 21,100 calories for the ballistic heat trasnfer. This is approximately 10 per cent of the energy released by the powder and is 28 per cent of the kinetic energy imparted to the projectile.

Comparison with Theoretical Surface Temperatures

The work of Nordheim, Soodak, and Nordheim (5) has been selected for an initial comparison of theoretical heat transfer predictions with the experimental measurements. This work uses a simplified ballistic system in which heat loss to the gun barrel is accounted for in the energy equation by an adjusted value for the specific heat ratio. Local velocities determined from the ballistic solution are used in the unmodified form of the Reynolds analogy to calculate local heat transfer coefficients. That is, $h = 1/2\lambda c_p \rho u$, where h is the heat transfer coefficient, λ the hydrodynamic friction factor, ρ the density assumed uniform behind the projectile, and u the local gas velocity.

By use of appropriate gun constants and the assumption of uniform powder distribution behind the projectile during burning, the results shown in Fig. 10 were obtained. The value of 0.004 for λ was selected first, since this is of the order of magnitude recommended. It should be mentioned that the Nordheim, Soodak, and Nordheim ballistic solution did

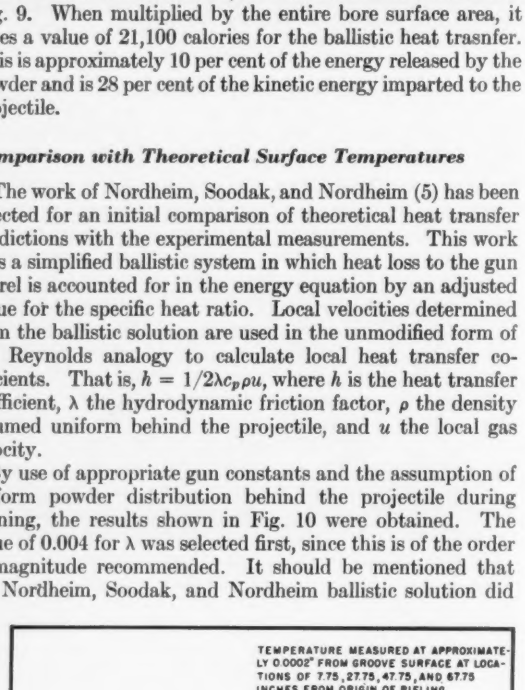

Fig. 10 Comparison of experimental surface temperature records with curves from the Nordheim theory

not predict the time when the temperature rise shown at the first thermocouple occurred. They assume that the projectile starts to move as soon as the pressure starts to rise, and as would be anticipated, the theory predicts the projectile reaches the No. 1 position early. However, since heat transfer is treated somewhat independently of the ballistics, the theoretical curves have been moved over to coincide with the experimental curves.

As will be noted, with λ equal to 0.004, the peak temperature predicted at the No. 1 thermocouple location is about 200 C lower than the experimental value. At the second location, the deficiency is not quite as great, and at the No. 4 location, the predicted value is higher than the experimental. This trend is quite likely due primarily to the assumption of uniform gas temperature and pressure behind the projectile.

To investigate the effect of a higher λ, the curves for a value of 0.007 were determined at the No. 1 and No. 2 position. Although relatively good agreement resulted at the No. 1 location, the theoretical curve rises to a higher maximum than the experimental at the No. 2 location. The agreement at the Nos. 3 and 4 positions is not as good as with $\lambda = 0.004$. It is interesting to note that the theoretical curve rises faster than the experimental in this case, although extrapolation of the experimental curve to the actual surface would reduce the apparent difference.

It may be noted that 0.007 is not an unreasonable value for λ, but it should also be pointed out that adjustment of the value of λ to give reasonable agreement with the experimental data does not necessarily demonstrate the validity of the underlying theory and assumptions. Further study of the problem is obviously necessary, particularly in regard to use of the more accurate ballistic system. It is interesting and significant to note, however, that the predictions are certainly of the right order of magnitude, and that steady-state theory can apparently be utilized successfully even for such rapidly changing phenomena.

Summary

In summarizing this work, it may be said that a method of measuring rapidly changing temperatures very close to a gas-metal interface has been redemonstrated. The heat transfer responsible for this temperature variation can be calculated quite easily when semi-infinite solids requirements are satisfied. The comparison of theoretical bore-surface temperatures with experimental records is encouraging, but requires further study.

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Low-Frequency Combustion Stability of Liquid Rocket Motor With Different Nozzles[1]

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The effect of the unsteady flow in the supercritical nozzle on the stability of small low-frequency pressure oscillations in the combustion chamber of a liquid rocket motor is investigated. It is found that, for a monopropellant rocket, the effect is simply an increase of the gas residence time in the combustion chamber, with the result that the critical value of the time lag for neutral oscillations is increased (stabilizing) and that the critical frequency is decreased. This is interpreted physically as the volumetric effect of the nozzle in increasing the capacity of the combustion chamber to store the burned gas. For some simple nozzles, it is shown that about nine tenths of the converging portion of the nozzle volume should be added to the chamber volume in evaluating the gas residence time. For bipropellant rockets, the situation is slightly more complicated. However, the qualitative trend of the effect of the nozzle is still the same as in the case of a monopropellant rocket. The dissipation of the energy of the low-frequency disturbances in the combustion chamber due to the out flow through the nozzle is of secondary importance as compared with this volumetric effect. This last fact is in sharp contrast with the effect of the nozzle on high-frequency oscillations of the acoustic type in the combustion chamber, in which case the volumetric effect is secondary, while its effect in dissipating the energy of the disturbances is of primary importance.

I Introduction

PREVIOUS analyses of low-frequency oscillations (1–7)[3] are made on the assumption of quasi-steady gas flow in deLaval nozzle through which combustion gases are accelerated and ejected at supersonic speeds. The boundary condition as deduced from this quasi-steady flow assumption is that the Mach number of the gas flow entering the deLaval nozzle is constant so that the rate of flow of burned gas out of the combustion chamber into the deLaval nozzle is directly proportional to the stagnation pressure and inversely proportional to the square root of the stagnation temperature of the burned gas entering the nozzle. Tsien (8) questioned the validity of this assumption and analyzed the transfer function of the nozzle for several special cases. Crocco (9) extended Tsien's treatment with linear steady-state velocity distribution in subsonic portion of the nozzle and determined the specific acoustical admittance ratio of the nozzle flow for considerable range of the reduced frequency parameter β. The results show that for small values of β the real part of the admittance ratio is essentially constant and is equal to the value corresponding to that of quasi-steady nozzle flow. However, the imaginary part of the admittance ratio is directly proportional to the reduced frequency β, and the rate of increase of the imaginary part with β is quite considerable, especially when the entering Mach number is small, as is for the practical case. Furthermore, the magnitude of β for chugging frequencies with a conventional nozzle is not really very small but is of the order of one tenth and can be considerably bigger if the deLaval nozzle is exceptionally long. The object of the present paper is to investigate the effect of the deviation of the nozzle flow from being quasi-steady on the stability of low-frequency oscillation on liquid propellant rockets.

II Monopropellant Rocket

The status in the combustion chamber of a liquid propellent rocket is extremely complicated. For simplicity, we shall first consider the monopropellant case and adopt the following assumptions in accordance with previous authors without further discussion.

(a) The gas pressure inside the combustion chamber is practically uniform everywhere in the combustion chamber and at any instant. In unsteady-state operation, the chamber pressure oscillates about the mean or steady-state value as a whole.

(b) The adiabatic flame temperature of the burned gas is assumed for monopropellant case to be constant and independent of the small variations of pressure under which combustion takes place. The temperature of the burned gas is further assumed to remain unchanged throughout its motion in the combustion chamber irrespective of the chamber pressure oscillation.

(c) The time lag of all the propellant elements are assumed to be the same.

The first two assumptions enable us to neglect the equations of conservation of momentum and of energy for the flow of the burned gas in the combustion chamber. The dynamics of the burned gas flow is thus governed only by the equation of mass balance; that is, the rate of burned gas generation $\dot{m}_b(t)$ must be equal to the sum of the rate of ejection $\dot{m}_e(t)$ of burned gas out of the combustion chamber into the deLaval nozzle and the rate of accumulation dM_g/dt of burned gas in the combustion chamber. All notations are adopted from Crocco (4) except where new symbols are necessary. The equation of mass balance is reduced to the following dimensionless form:

$$\frac{d\varphi}{dz} + \mu_e(z) = \mu_b(z) \qquad [2.1]$$

where $z = t/\theta g$ is the reduced time with

$$\theta g = \frac{g}{\gamma}\left(\frac{2}{\gamma+1}\right)^{-(\gamma+1)/(\gamma-1)} \frac{L^*}{C^*}$$

= the average gas residence time in the combustion chamber. φ, μ_b, and μ_e are the fractional variations of the chamber pressure, mass burning rate, and mass ejection rate, respectively.

We shall assume that the entire time lag is sensitive and the dependence of τ on pressure is defined as

$$\int_{t-\tau}^{t} p^n(t')dt' = \text{const}$$

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[3] Numbers in parentheses indicate References at end of paper.

where n is the index of interaction in terms of instantaneous pressure including the effect of temperature variations of the burned gas, etc. It has been shown (4) that

$$\mu_b = \mu_i(z - \delta) + n\,[\varphi(z) - \varphi(z - \delta)] \ldots\ldots [2.2]$$

where δ is the fractional variation of gas density in the combustion chamber, and μ_i is the fractional variation of the propellant injection rate.

The fractional variation of the mass flow rate out of the combustion chamber depends on the transfer function N_n of the deLaval nozzle with supersonic exit velocity. For quasi-steady nozzle flow and isentropic oscillations of the burned gas, we have

$$\mu_e = \frac{p'}{p} - \frac{1}{2}\frac{T'}{T} = \frac{\gamma + 1}{2\gamma}\varphi_e$$

with the nozzle transfer function based upon fractional pressure variation given as $(\gamma + 1)/2\gamma$ which is equal to unity when the temperature variation of the gas is neglected. The specific admittance ratio α_n is defined as the ratio of the fractional variation of gas velocity to that of gas density at the entrance of the deLaval nozzle and can be represented for low-frequency oscillations as

$$\alpha_n = \frac{\gamma - 1}{2} + ik\frac{\Omega}{\bar{u}_z} \ldots\ldots\ldots\ldots\ldots [2.3]$$

where Ω is the dimensional angular frequency of neutral oscillation, and $\bar{u}_z$ is the constant velocity gradient of the gas flow in the subsonic part of the nozzle. The constant k for isentropic oscillations can be obtained from (9) as

$$k = -\left(\frac{1}{2}\frac{\ln z_e}{1 - z_e} + \frac{\gamma - 1}{4}\right) \ldots\ldots\ldots\ldots [2.4]$$

in which $(\gamma - 1)/4$ can be neglected in accordance with assumption (b). The quantity z_e is defined as

$$z_e = \frac{\dfrac{\gamma + 1}{2}M_e^2}{1 + \dfrac{\gamma - 1}{2}M_e^2}$$

with M_e representing the Mach number of the burned gas entering the nozzle. The quantity z_e is usually less than 0.1 for conventional liquid rockets, and k is slightly bigger than unity. The transfer function of the mass flow based on fractional pressure variation at the entrance is

$$N_n = \frac{1}{\gamma}\cdot[1 + \alpha_n] = \frac{\gamma + 1}{2\gamma} + i\frac{k}{\gamma}\frac{\Omega}{\bar{u}_z}$$

which reduces to

$$N_n = 1 + ik\frac{\Omega}{\bar{u}_z} = 1 + ib\cdot\omega$$

when $\gamma = 1$ under the assumption of negligible temperature variation. The proportionality constant b is dimensionless and is equal to $k/(\theta g\cdot\bar{u}_z)$. When the steady-state velocity in the subsonic portion of the nozzle is linear, the value of k is given by Equation [2.4] and the factor b is given as

$$b = \frac{k}{\theta g \bar{u}_z} = -\frac{1}{2}\frac{\ln z_e}{1 - z_e}\cdot\frac{1}{\bar{u}_z}\cdot\frac{1}{\theta g} \ldots\ldots\ldots\ldots [2.5]$$

It is conjectured that for practical nozzle shape where the velocity distribution is not linear, this constant b will still be independent of the frequency of oscillation and of the order of magnitude, say two tenths. Thus the absolute magnitude of the transfer function will not be significantly different from unity, which is the quasi-steady value, but the phase lead of the mass flow oscillation is quite considerable even for low frequency oscillations.

If we write the nozzle transfer function in operational form $N_n = 1 + b(d/dz)$ while investigating the stability of near neutral oscillations of the exponential type, then

$$\mu_e = \left(1 + b\frac{d}{dz}\right)\varphi_e = \left(1 + b\frac{d}{dz}\right)\varphi \ldots\ldots\ldots [2.6]$$

where φ_e is replaced by φ since we assumed that the fractional variation of pressure at any instant is the same everywhere in the combustion chamber. Introducing Equations [2.2] and [2.6] into Equation [2.1], we obtain the equation of mass balance as

$$\underbrace{\frac{d\varphi}{dz}}_{\text{Accumulation}} + \underbrace{\left(1 + b\frac{d}{dz}\right)\varphi}_{\text{Ejection}} = \underbrace{\mu_i(z - \delta) + n[\varphi(z) - \varphi(z - \delta)]}_{\text{Generation}} \ldots\ldots\ldots [2.7]$$

The formulation for the analysis of the oscillation problem will require a relation between the fractional variation of the injection rate μ_i and the fractional variation of chamber pressure. This relation depends upon the dynamic characteristics of the feeding system in response to the chamber pressure variation. The dynamics of the feeding system will be formulated following Crocco (4) and Tsien (5), with the following assumptions:

(a) The pressure drop due to wall friction in feed line is negligibly small compared to the over-all drop of the feeding system.

(b) The effect of the elasticity of the feeding line can be represented by an equivalent concentrated spring capacitance C_l located at a distance $y{\cdot}l$ downstream of the pump delivery, where l is the equivalent length of the feeding line. The spring constant χ of the capacitance is defined as the change in volume of the feed line produced by unit pressure rise over the entire feed line.

(c) The feed pump responds to oscillations of delivery pressure instantaneously and the fractional variation of mass delivery rate is directly proportional to the fractional variation of the delivery pressure with the proportionality constant D defined as

$$\frac{\Delta\bar{p}}{\bar{p}} = -D\frac{\Delta\dot{m}}{\bar{\dot{m}}} \ldots\ldots\ldots\ldots\ldots [2.8]$$

and D is assumed real and therefore can be evaluated from the steady-state performance curve of the pump.

(d) A control capacitance C_c excited by a feedback circuit is introduced just upstream of the injector. The characteristics of the feedback circuit are described by the transfer function $F(d/dz)$ as

$$F\left(\frac{d}{dz}\right)\varphi = \frac{C_c}{\bar{\dot{m}}\theta g} \ldots\ldots\ldots\ldots\ldots [2.9]$$

A schematic diagram of the liquid rocket is given in Fig. 1. A

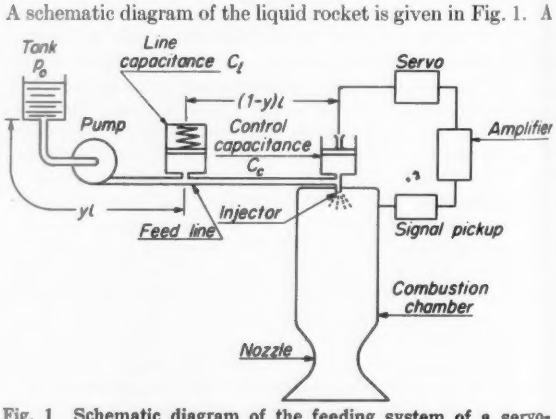

Fig. 1 Schematic diagram of the feeding system of a servo-controlled liquid propellent rocket motor

straight forward process of elimination leads to the following dimensionless equation of the feeding system dynamics relating φ and μ_i as

$$\left\{P\left[1 + DE\left(P + \frac{1}{2}\right)\frac{d}{dz} + JEy\frac{d^2}{dz^2}\right] + \left[D\left(P + \frac{1}{2}\right)\frac{d}{dz} + J\frac{d^2}{dz^2} + DJE(1 - y)\left(P + \frac{1}{2}\right)\frac{d^3}{dz^3} + J^2Ey(1 - y)\frac{d^4}{dz^4}\right]F\left(\frac{d}{dz}\right)\right\}\varphi +$$
$$\left\{\left[1 + D\left(P + \frac{1}{2}\right)\right] + \left[DE\left(P + \frac{1}{2}\right) + J\right]\frac{d}{dz} + \left[DJE(1 - y)\left(P + \frac{1}{2}\right) + JEy\right]\frac{d^2}{dz^2} + J^2Ey(1 - y)\frac{d^3}{dz^3}\right\}\mu_i = 0 \ldots [2.10]$$

where $P = \bar{p}/2\Delta\bar{p}$ is the pressure drop parameter, a relative measure of the pressure drop across the injector. $E = \frac{2\Delta\bar{p}\rho_0\chi}{\bar{m}\theta g}$ is the elasticity parameter, a ratio of the rate of mass accumulation in the line capacitance due to a rate of pressure increase of $2\Delta\bar{p}/\theta g$ to the mean mass flow rate of the system. $J = \frac{l\bar{m}}{2\Delta\bar{p}\cdot A_1\theta g}$ is the inertia parameter, a ratio of the time required to accelerate a given element from rest to the state of motion in the feed line under the pressure drop of $2\Delta\bar{p}$ as compared to the gas residence time θg.

Equations [2.7] and [2.10] are to be solved simultaneously. The correction factor b for the phase lead component of the nozzle transfer function appears only in Equation [2.7] and can be absorbed by defining a new characteristic time $(1 + b)\ \theta g = \theta g'$ instead of the average gas residence time θg, as defined by Crocco. The dimensionless parameters which involve the characteristic time should, of course, be correspondingly modified. Thus

$$\left.\begin{aligned} z' &= t/\theta g' = z/(1 + b) \\ \delta' &= \delta/\theta g' = \delta/(1 + b) \\ E' &= 2\Delta\bar{p}\rho_0\chi/\bar{m}\theta' g = E/(1 + b) \\ J' &= l\bar{m}/2\Delta\bar{p}\cdot A\cdot\theta g' = J/(1 + b) \\ F'\left(\frac{d}{dz'}\right) &= C_e/\bar{m}\theta g' = F\left(\frac{d}{dz}\right)/(1 + b) \\ \text{and}\quad \omega' &= \Omega\cdot\theta g' = (1 + b)\omega \end{aligned}\right\} \ldots [2.11]$$

Those dimensionless parameters P, D, and n which do not involve characteristic time remain unchanged.

With this transformation, Equations [2.7] and [2.10] can be easily verified to be explicitly independent of b and are identical with the form of these equations with $b = 0$ corresponding to a "very short nozzle" where the quasi-steady nozzle flow assumption is approximately valid. For different deLaval nozzles the values of b will be different, but its effect can be accounted for simply by changing the characteristic time from θg to $\theta g(1 + b)$. The solution of the characteristic equation remains identical in terms of the dimensionless quantities defined in Equations [2.11]. Therefore the solutions and the stability boundaries given by previous authors for the case $b = 0$ in terms of these dimensionless quantities represent the similar or the universal solutions for rockets with given feeding system and combustion chamber but different deLaval nozzles.

The characteristic equation for neutral oscillations with $d/dz' = i\omega'$ then becomes

$$(i\omega' + 1 - n + ne^{-i\delta'\omega'})\left\{\left[1 + D\left(P + \frac{1}{2}\right)\right] + \left[DE\left(P + \frac{1}{2}\right) + J\right]i\omega' - \left[DJ'E'(1 - y)\left(P + \frac{1}{2}\right) + J'E'y\right]\omega'^2 - iJ'^2E'y(1 - y)\omega'^3\right\} =$$
$$\left[1 + DE'\left(P + \frac{1}{2}\right)i\omega' - J'E'y\omega'^2\right] + \left[D\left(P + \frac{1}{2}\right) + J'i\omega' - DJ'E'(1 - y)\left(P + \frac{1}{2}\right)\omega'^2 - iJ'^2E'y(1 - y)\omega'^3\right]i\omega'F'(i\omega') \ldots [2.12]$$

From Equation [2.12], we observe that the dimensionless quantities E and J occur only as $E'\omega_*'$ and $J'\omega_*'$ which are independent of b and equal to $E\omega$ and $J\omega$, respectively. The transfer function $F(i\omega')$ enters Equation [2.12] only as $i\omega'F'(i\omega') = \frac{dC_e}{dt}/\bar{m} = i\omega F(i\omega)$ which is independent of the selection of the characteristic time. The quantity $\omega'\delta'$ which represents 2π times the ratio of time lag to the period of oscillation is also independent of b with $\omega_*'\delta_*' = \omega_*\delta_*$. The critical values of $\delta_*'\omega_*'$ and ω_*' are therefore functions of dimensionless quantities which are all independent of b and are the same as $\delta_*\omega_*$ and ω_* determined with $b = 0$. Therefore the effect of the phase lead component $ib\omega$ of the nozzle transfer function can be directly obtained without determining the similar or the universal solution ($b = 0$) of the characteristic equation. Since ω_*' and $\delta_*'\omega_*'$ are constants for any values of b and since

$$\left\{\begin{aligned} \omega_*' &= \Omega_*\cdot\theta g(1 + b) \\ \omega_*'\delta_*' &= 2\pi\frac{\bar{\tau}_*}{T} = \Omega_*\cdot\bar{\tau}_* = \omega_*'\frac{\bar{\tau}_*}{\theta g}/(1 + b) \end{aligned}\right.$$

we see that for increasing b or larger phase lead, the dimensional frequency Ω_* of the neutral oscillation in cycles per second is decreased and the dimensional critical time lag $\bar{\tau}_*$ is increased. It can therefore be concluded that the phase lead component of the nozzle transfer function tends to stabilize the system toward low-frequency oscillations, and larger phase lead component results in larger stabilizing effect is increasing the critical time lag.

III Bipropellant Rockets

In bipropellant rocket systems the dynamic behaviors of the feeding systems of the oxidizer and the fuel are in general different. The variations of the injection rates of oxidizer and of fuels in response to the same chamber pressure variation are different with a consequent variation in the oxidizer-fuel or mixture ratio $r = \dot{m}_0/\dot{m}_f$. The adiabatic flame temperature of a given propellant combination depends to a certain extent on the mixture ratio. The stagnation temperature of the burned gas at a given position in the combustion chamber therefore varies with time as the chamber pressure oscillates and the stagnation temperature of the burned gas at different positions in the chamber at a given instant is also different. This variation of stagnation temperature of burned gas, which is absent in monopropellant rockets, must be taken into account in formulating the equation of mass balance in the combustion chamber for bipropellant rockets. By assuming that all combustion takes place practically at the injector end, and that all propellant elements have the same gas residence time θg, during which all these particles travel from the injector end to the combustion chamber exit and preserve their respective temperature at the instant when they were generated, Crocco (4) found the following expressions. For the fractional burning rate perturbation μ_b

$$\frac{d}{dz}\left(\frac{Mg}{\overline{Mg}}\right) + \mu_e = \mu_b \ldots [3.1]$$

$$\mu_b = \mu_i(z - \delta) + n[\varphi(z) - \varphi(z - \delta)] \ldots [3.2]$$

with

$$\mu_i = \left(\frac{1}{2} + H\right)\mu_0 + \left(\frac{1}{2} - H\right)\mu_f \ldots [3.3]$$

and

$$H = \frac{1}{2}\frac{\bar{r} - 1}{\bar{r} + 1}$$

For the rate of mass accumulation

$$\frac{d}{dz}\left(\frac{Mg(z)}{\bar{M}g}\right) = \frac{d\varphi}{dz} - 2K[\mu_o(z - \delta - 1) - \mu_f(z - \delta - 1)] + 2K[\mu_o(z - \delta) - \mu_f(z - \delta)] \quad [3.4]$$

For the fractional variation of ejection rate evaluated under the assumption of quasi-steady nozzle flow

$$\mu_e = \varphi(z) - K[\mu_o(z - \delta - 1) - \mu_f(z - \delta - 1)] \quad [3.5]$$

where $2K = \frac{\bar{r}}{\bar{T}g}\frac{d\bar{T}g}{dr}$ represents the dimensionless slope of the adiabatic flame temperature curve for different mixture ratio.

Just like the monopropellant case, the fact that the flow of burned gas in the nozzle is not quasi-steady only modifies μ_e, not the other terms. But owing to the variation of the stagnation temperature of the burned gas, there is also an entropy oscillation of the burned gas entering the nozzle. The specific admittance ratio ν_e/δ_e is given by Crocco (9) as

$$\frac{\nu_e}{\delta_e} = \frac{\gamma - 1}{2}\frac{\theta}{\theta - \sigma} + i\frac{\Omega}{\bar{u}_z}\left\{-\frac{\theta}{\theta - \sigma}\left[\frac{1}{2}\frac{\ln z_e}{1 - z_e} + \frac{\gamma - 1}{4}\right] + \frac{\sigma}{\theta - \sigma}\left[\frac{\gamma + 1}{4\gamma}\frac{\ln z_e}{1 - z_e} + \frac{\gamma - 1}{4\gamma}\right]\right\} + O\left(i\frac{\Omega}{\bar{u}_z}\right)^2 \quad [3.6]$$

for a deLaval nozzle with linear steady-state velocity in the converging portion, where θ and σ are the amplitudes of the temperature and the entropy oscillations at the entrance of the nozzle, respectively. In accordance with the assumption that the temperature oscillation of the burned gas in the combustion chamber is neglected when the oscillation is isentropic, $\gamma - 1$ is neglected as compared to unity. Thus the first approximation of phase lead component of the admittance ratio becomes $-\frac{1}{2}\frac{\ln z_e}{1 - z_e}\frac{\Omega}{\bar{u}_z}$ which is identical with the value given in Equation [2.4] for monopropellant case. That the phase lead component is independent of the ratio σ/θ of the amplitude of entropy to that of the temperature oscillation is correct only when $\gamma = 1$. Since $\gamma - 1$ is usually 0.2 or 0.3 for practical combustion gases the ratio of σ/θ may be of importance, and the magnitude of this phase lead component will depend on many thermodynamic properties of the combustion gases even for an idealized nozzle with linear steady state velocity distribution.

The transfer function for the mass flow through the nozzle is, for the bipropellant case,

$$\frac{\mu_e}{\varphi_e} = N_n = (1 + \alpha_n)\left(1 - \frac{\theta_e}{\varphi_e}\right) \quad [3.7]$$

Thus in accordance with the assumption of $\gamma \cong 1$, we have

$$\mu_e = \left(1 + b\frac{d}{dz}\right)(\varphi_e - \theta_e) \quad [3.8]$$

where $b = -\frac{1}{2}\frac{\ln z_e}{1 - z_e}\frac{1}{\theta g \bar{u}_z}$ which is the same as for monopropellant case. The expression for $\mu_e = \varphi_e - \theta_e$, when $b = 0$ is given by Equation [3.5]. If the steady-state gas velocity in the nozzle is not linear, we would of course expect a slight change in the expression and the value of b. The equation of mass balance becomes

$$(1 + b)\frac{d\varphi}{dz} + (1 - n)\varphi + n\varphi(z - \delta) =$$

$$\left(-2K + \frac{1}{2} + H\right)\mu_o(z - \delta) - \left(-2K - \frac{1}{2} + H\right)\mu_f(z - \delta) + K\left(3 + b\frac{d}{dz}\right)[\mu_o(z - \delta - 1) - \mu_f(z - \delta - 1)] \quad [3.9]^4$$

It is no longer possible to reduce Equation [3.9] to the form with $b = 0$ by changing the characteristic time, as was done in previous section. The effect of a phase lead component of the nozzle transfer function on the stability of a bipropellant motor can be determined in a simple manner only after introducing further approximation. The dimensionless slope K of the adiabatic flame temperature curve is usually a rather small fractional quantity, of the same order as b, except when the liquid rocket is designed to operate at very lean or very rich mixture ratio. Thus, to the first approximation of the order of b or K, the term

$$b\frac{d\theta_e}{dz} = Kb\frac{d}{dz}[\mu_o(z - \delta - 1) - \mu_f(z - \delta - 1)]$$

may be neglected as compared with other terms either of the order of unity or of b or K in Equation [3.9] in determining the qualitative trend of the effect of the phase lead component of the nozzle transfer function. After dropping this term from Equation [3.9], it can be seen that the new definition of the characteristic time $\theta g(1 + b)$ will reduce the equation of mass balance to the form by putting $b = 0$. The two equations of the dynamics of the fuel and the oxidizer feeding system, each of them of the form of Equation [2.10], can also be reduced with the new dimensionless parameters as defined in Equation [2.11].

With this additional approximation of neglecting $b(d\theta_e/dz)$, the qualitative conclusion with regard to the increasing stabilizing effect of larger phase lead component of the nozzle transfer function, as deduced in previous section for the monopropellant case, holds for the bipropellant case as well. The stabilizing effect appears as the increase of the critical time lag for neutral oscillation in the liquid rockets. For the bipropellant case, however, the factor b of the phase lead component will in general not only be a function of the geometry of the nozzle and the specific heat ratio γ of the combustion gases as for the monopropellant rocket, but may also depend on the magnitudes of K and σ/θ. The entropy variation of the burned gas due to the variation of the stagnation temperature can no longer be neglected as was in the monopropellant case where the entropy variation is essentially due to different dissipative agents. Furthermore, the neglect of the term $b((d\theta_e)/(dz))$, which involves all the feeding system parameters, may result in a small dependence of the apparent value of b on feeding system constants.

IV Physical Aspects and Discussion of Results

The fact that the existence of a phase lead component of the nozzle transfer function is in effect an increase of the gas residence time needs some clarification. If we examine the analysis (8) and (9) for the nozzle admittance ratio, we see that the phase lead component arises because of the inertia of the gas. When the pressure in the chamber is increased, the inertia of the gas in the subsonic portion of the nozzle leads to an accumulation of burned gas in addition to the accumulation of gas in the combustion chamber. In other words, the storaging capacity of the chamber is augmented by the subsonic portion of the nozzle. It is therefore natural, though it may not be quite right, to think that the increase of the characteristic time due to the phase lead component simply means that the volume $\bar{V}_n$ of the subsonic portion of the nozzle should be added to the volume $\bar{V}_c$ of the combustion chamber in determining the characteristic time. It should, however, be noted that the pressure and temperature level of the gas in the nozzle is decreasing continuously toward the throat, and that, while the chamber pressure varies, the pressure in the nozzle varies in a different manner. Therefore the capability of the volume $\bar{V}_n$ of the subsonic portion of the nozzle in accumulating burned gas in response to an increase in the chamber pressure is different from the capability of an equal volume $\bar{V}_n$ situated in the combustion chamber. Let us de-

[4] The author is indebted to Prof. L. Crocco for calling his attention to the sign mistake in Equation [10.1] in Reference (4) which is used in deducing Equation [3.9].

fine a coefficient ϵ of the average effectiveness of the nozzle volume as compared to chamber volume in the determination of the gas residence time as

$$\theta g' = \theta g\left(\frac{\bar{V}_c + \bar{V}_n\epsilon}{\bar{V}_c}\right) = \theta g(1 + b)$$

then

$$\epsilon = \frac{b\bar{V}_c}{V_m} = \frac{b\theta g \cdot \bar{m}}{\bar{V}_n \cdot \rho_c} \quad \text{[5.1]}$$

For the case of a nozzle with linear steady-state velocity distribution in the subsonic portion and for isentropic oscillations, the coefficient ϵ is obtained from Equations [2.4], [2.5], and [5.1] as

$$\epsilon = \left(-\frac{\ln z_e}{1 - z_e} - \frac{\gamma - 1}{2}\right) \Big/ \int^1 \left(1 - \frac{\gamma - 1}{\gamma + 1} z\right)^{-1/\gamma - 1} z^{-1} dz$$

$$\cong \left[-\frac{\ln z_e}{1 - z_e} - \frac{\gamma - 1}{2}\right] \cdot \Big/ \left[-\ln z_e + \frac{1}{\gamma + 1}\left\{(1 - z_e) + \frac{\gamma}{\gamma + 1}\frac{1 - z_e^2}{2 \cdot 2!}\right.\right.$$

$$\left.\left. + \frac{\gamma(2\gamma - 1)}{(\gamma + 1)^2}\frac{1 - z_e^3}{3 \cdot 3!} + \frac{\gamma(2\gamma - 1)(3\gamma - 2)}{(\gamma + 1)^3}\frac{1 - z_e^4}{4 \cdot 4!} + \right.\right. \quad \text{[5.2]}$$

which is a function of contraction ratio A_*/A_e of the nozzle alone. Sample calculations for $\gamma = 1.20$ with $z_e = 0.20, 0.10$, and 0.05 corresponding to Mach number $M_e = 0.4, 0.3$, and 0.2, respectively, at the entrance section, the coefficient ϵ is equal to 0.93, 0.89, and 0.87 for each of the three cases. The variation of ϵ for such a wide range of entrance Mach number variation is rather insignificant and the magnitude of ϵ can be approximately taken as 0.9.

Crocco has shown that the admittance ratio of a nozzle with velocity substantially linear upstream of the sonic throat but not linear in the neighborhood of the entrance can best be approximated by the ratio of the nozzle where the velocity distribution is linear with velocity gradient equal to that at the sonic throat of the given nozzle. Under such circumstances, the magnitude of ϵ would be expected to be approximately 0.9. However, for nozzles whose velocity distribution is far from being linear, we have no idea as to the relation of b with the volume $\bar{V}_n$, and the value of ϵ may be significantly different from 0.9.[5] It should be noticed that, while the concept of increasing available chamber volume leads to a simple and convenient interpretation of the stabilizing effect of the nozzle through the increase of characteristic time, this concept is not helpful quantitatively. Either from the previous physical picture or from the dependence of b on the entering Mach number and the velocity gradient in nozzles of given geometrical shape, the stabilizing effect of the phase lead component of the transfer function is larger: 1 if the entering Mach number or the contraction ratio is decreased; 2 if the length of the nozzle is increased. The stabilizing effect appears as an increase in the critical time lag $\bar{\tau}_*$ which is accompanied by a corresponding decrease in the frequency of neutral oscillation.

It should be emphasized that, from the analysis, the "unconditional stability" or the stability of the system regardless of the time lag, as expressed by the minimum value $n_{\min}$ of the interaction index n compatible with any unstable low-frequency oscillations, is *not* affected. The nozzle stabilizing effect toward low-frequency oscillations is essentially a volumetric effect, which is fundamentally different from the stabilizing effect of the nozzle toward high frequency oscillation, in which case the value of $n_{\min}$ is increased in addition to the reduction in unstable range of the values of $\bar{\tau}$. Nozzle stabilizing effect toward high-frequency oscillation is largely due to the increasing dissipation of the energy of the disturbance due to the unsteady flow through the nozzle. This dissipation, is negligibly small for low-frequency oscillations.

[5] Since the completion of this paper, the determination of the nozzle specific admittance ratio α_w has been extended considerably. For the expression qb for conventional rocket nozzles, the reader is referred to Appendix B of Reference (10).

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Heat Transfer to a Cylinder for the Free Molecule Flow of a Nonuniform Gas

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Theoretical relations are obtained for the heat transfer to a transverse cylinder for the free molecule flow of a nonuniform gas. The cylinder diameter is assumed to be small compared to the molecular mean free path, and the gas flow is assumed to have arbitrary viscous stress and heat flux terms present. The effect of these nonuniformities on the heat transfer to the wire and its equilibrium temperature are determined theoretically. A possible application is in connection with the use of such a wire as a probe for surveying boundary layers, shock waves, etc. Results are a direct extension of the calculations presented in (1).[3]

In a previous paper (1) the authors presented the theoretical calculations for predicting the aerodynamic force on a cylinder under conditions of free molecule flow in a nonuniform gas. It is the purpose of this note to extend these calculations to the case of heat transfer. The method and notation will be the same as in (1). The results are confined to the case of a monatomic gas.

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Following the general method of Stalder, et al. (2), the energy balance for a differential area dA, in the absence of radiation, is written

$$dE_i = dE_r + dQ \qquad [1]$$

where dE_i is the incident energy flux, dE_r the re-emitted energy flux, and dQ the net heat loss per unit time from the surface element. From the definition of the thermal accommodation coefficient α

$$\alpha = \frac{dE_i - dE_r}{dE_i - dE_w} \qquad [2]$$

where dE_w is the energy flux which would be re-emitted from the surface if all molecules were re-emitted with a Maxwellian distribution corresponding to the surface temperature T_w, one obtains

$$\frac{1}{\alpha}\,dQ = dE_i - dE_w \qquad [3]$$

The incident energy flux per unit area is

$$\frac{dE_i}{dA} = \frac{m}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty}(u'^2 + v'^2 + w'^2)u'f\,du'\,dv'\,dw' \qquad [4]$$

where the distribution function f is taken from Grad (3)

$$\left.\begin{aligned} f = f^0\Bigg[1 + \frac{1}{2pRT}\Bigg\{&p_{xx}(u - U)^2 + p_{yy}v^2 + p_{zz}w^2 \\ &- 2\tau_{xy}(u - U)v - 2\tau_{xz}(u - U)w - 2\tau_{yz}vw \\ &- 2\left[1 - \frac{(u - U)^2 + v^2 + w^2}{5RT}\right][q_x(u - U) + \\ &q_yv + q_zw]\Bigg\}\Bigg] \end{aligned}\right\} \qquad [5]$$

with

$$f^0 = \frac{\rho}{m(2\pi RT)^{3/2}}\,e^{-\frac{(u - U)^2 + v^2 + w^2}{2RT}} \qquad [6]$$

The symbols, p, R, T, U, p_{xx}, p_{yy}, p_{zz}, τ_{xy}, τ_{xz}, τ_{yz}, q_x, q_y, q_z, refer to the gas pressure, gas constant, temperature, velocity, and the normal and tangential stress and heat flux components. The symbols m, u, v, w, denote the molecular mass and velocity components. The primed and unprimed coordinate systems are indicated in Fig. 1. One has

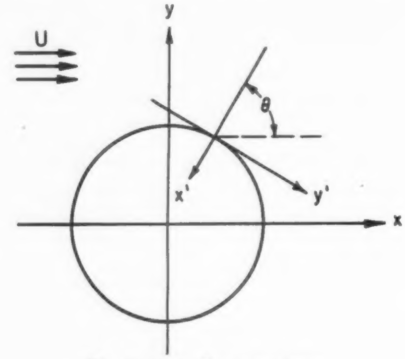

Fig. 1 Coordinate systems

$$\left.\begin{aligned} u &= -u'\cos\theta + v'\sin\theta \\ v &= -u'\sin\theta - v'\cos\theta \\ w &= w' \end{aligned}\right\} \qquad [7]$$

The energy flux per unit area of diffusely reflected molecules is

$$\frac{dE_w}{dA} = 2mRT_w\frac{dN_w}{dA} = 2mRT_w\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty}u'f\,du'dv'dw' \qquad [8]$$

where dN_w is the number flux of re-emitted (or incident) molecules. Combining Equations [3], [4], [5], and [8], and integrating over a unit length of a cylinder of diameter d, one has

$$\begin{aligned} \frac{1}{\alpha}Q = \frac{\sqrt{\pi}\,d\rho URT}{4se^{s^2/2}}\Bigg[&\{(2s^4 + 7s^2 + 4)I_0(s^2/2) + (2s^4 + 5s^2)I_1(s^2/2)\} \\ &+ \frac{p_{xx}}{4p}\{(8s^2 + 6)I_0(s^2/2) + (8s^2 - 4)I_1(s^2/2)\} \\ &+ \frac{p_{yy}}{4p}\{(2s^2 + 6)I_0(s^2/2) + (2s^2 + 4)I_1(s^2/2)\} \\ &+ \frac{q_xs^2}{5pU}\{10I_0(s^2/2) + 12I_1(s^2/2)\}\Bigg] \\ &- \frac{\sqrt{\pi}d\rho URT_w}{se^{s^2/2}}\Big[\{(1 + s^2)I_0(s^2/2) + s^2I_1(s^2/2)\} \end{aligned}$$

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[3] Numbers in parentheses indicate References at end of paper.

$$+\frac{p_{xx}}{4p}\{I_0(s^2/2)-I_1(s^2/2)\}+\frac{p_{yy}}{4p}\{I_0(s^2/2)+I_1(s^2/2)\}$$
$$-\frac{q_x s^2}{5pU}\{I_0(s^2/2)-I_1(s^2/2)\}\Bigg] \quad \ldots\ldots [9]$$

where I_0 and I_1 are Bessel functions, and s is the molecular speed ratio

$$s=\frac{U}{\sqrt{2RT}}=\sqrt{\frac{\gamma}{2}}\,M \quad \ldots\ldots [10]$$

The results are confined to the case of a monatomic gas, since there still exists a question as to the nature of the distribution function analogous to that given in Equation [5] but applying to a gas with internal degrees of freedom.

Denoting by T_{aw} the equilibrium cylinder temperature, one has

$$\frac{T_{aw}}{T}=H_0+\frac{p_{xx}}{p}H_{p_{xx}}+\frac{p_{yy}}{p}H_{p_{yy}}+\frac{q_x}{pU}H_{q_x} \quad \ldots [11]$$

where

$$H_0=\frac{(2s^4+7s^2+4)I_0(s^2/2)+(2s^4+5s^2)I_1(s^2/2)}{(4s^2+4)I_0(s^2/2)+4s^2I_1(s^2/2)}$$

$$H_{p_{xx}}=\frac{(2s^2+3/2)I_0(s^2/2)+(2s^2-1)I_1(s^2/2)\ -}{(4s^2+4)I_0(s^2/2)+\dfrac{H_0\{I_0(s^2/2)-I_1(s^2/2)\}}{4s^2I_1(s^2/2)}}$$

$$H_{p_{yy}}=\frac{(s^2/2+3/2)I_0(s^2/2)+(s^2/2+1)I_1(s^2/2)\ -}{(4s^2+4)I_0(s^2/2)+\dfrac{H_0\{I_0(s^2/2)+I_1(s^2/2)\}}{4s^2I_1(s^2/2)}} \quad \ldots [12]$$

$$H_{q_x}=\frac{2s^2I_0(s^2/2)+\dfrac{12s^2}{5}I_1(s^2/2)\ +}{(4s^2+4)I_0(s^2/2)+\dfrac{H_0\left\{\dfrac{4s^2}{5}I_0(s^2/2)+\dfrac{4s^2}{5}I_1(s^2/2)\right\}}{4s^2I_1(s^2/2)}}$$

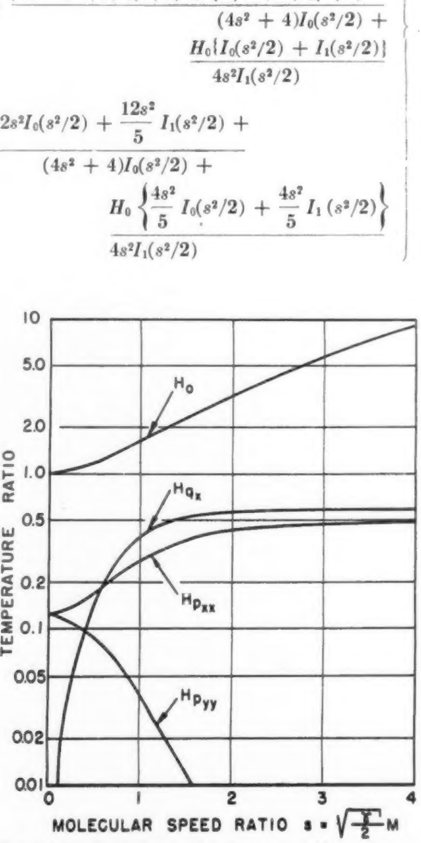

Fig. 2 Partial temperature ratios for nonuniform free molecule flow past a cylinder (monatomic gas)

$$\frac{T_{aw}}{T}=H_0+\frac{p_{xx}}{p}H_{p_{xx}}+\frac{p_{yy}}{p}H_{p_{yy}}+\frac{q_x}{pU}+H_{q_x}$$

These partial equilibrium temperature ratios are plotted in Fig. 2.

For the heat transfer case, one defines a Stanton number, St, for a cylinder of unit length

$$St=\frac{2Q}{5\pi d\rho UR(T_{aw}-T_w)} \quad \ldots\ldots [13]$$

Then

$$St=St_0+\frac{p_{xx}}{p}St_{p_{xx}}+\frac{p_{yy}}{p}St_{p_{yy}}-\frac{q_x}{pU}St_{q_x} \quad \ldots [14]$$

where

$$\frac{1}{\alpha}St_0=\frac{2}{5\sqrt{\pi s e^{s^2/2}}}\{(1+s^2)I_0(s^2/2)+s^2I_1(s^2/2)\}$$

$$\frac{1}{\alpha}St_{p_{xx}}=\frac{1}{10\sqrt{\pi s e^{s^2/2}}}\{I_0(s^2/2)-I_1(s^2/2)\}$$

$$\frac{1}{\alpha}St_{p_{yy}}=\frac{1}{10\sqrt{\pi s e^{s^2/2}}}\{I_0(s^2/2)+I_1(s^2/2)\}$$

$$\frac{1}{\alpha}St_{q_x}=\frac{2s}{25\sqrt{\pi e^{s^2/2}}}\{I_0(s^2/2)-I_1(s^2/2)\}$$

The corresponding partial Stanton numbers are given graphically in Fig. 3 for the case of diffuse reflection. The temperature

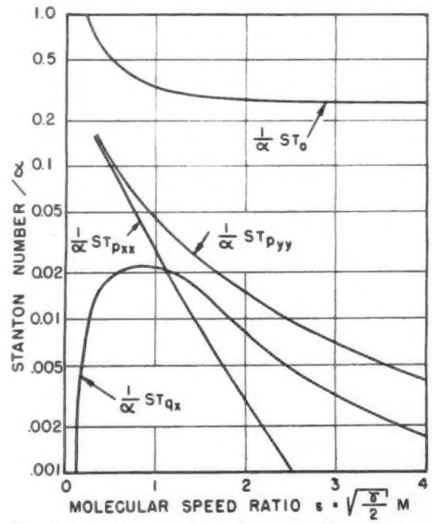

Fig. 3 Partial Stanton numbers for nonuniform free molecule flow past a cylinder (monatomic gas)

$$\frac{1}{\alpha}ST=\frac{1}{\alpha}ST_0+\frac{p_{xx}}{p}\frac{1}{\alpha}ST_{p_{xx}}+\frac{p_{yy}}{p}\frac{1}{\alpha}ST_{p_{yy}}-\frac{q_x}{pU}\frac{1}{\alpha}ST_{q_x}$$

ratio and Stanton number, H_0 and St_0, respectively, for the uniform case agree with those previously obtained by Stalder, Goodwin, and Creager (2).

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Thermal Properties of Commercial White Fuming Nitric Acid[1]

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The application of commercial white fuming nitric acid with various engine fuels as rocket propellants has created a demand for data on the physical properties of the acid. The data necessary for heat transfer and pressure drop calculations (thermal conductivity, viscosity, specific heat, density, and total pressure) were measured and are compiled for the temperature range from −30 to 300 F.

Introduction

THE use of white fuming nitric acid in processes which involve the transfer of heat has made necessary a knowledge of the thermal properties of the acid. The literature was searched for existing physical property information and then experiments were made to obtain additional data (1).[5]

Data were obtained for thermal conductivity, viscosity, specific heat, density, and total pressure for the liquid-phase acid under conditions at physical equilibrium over the approximate temperature range of −30 to 300 F. Since concentrated nitric acid decomposes rapidly at temperatures above 250 F, it would have been preferable to make the property determinations within a very short time interval—of the order of a few minutes. It is very difficult to make such determinations accurately within such a short time. Of all the experiments conducted, only the total-pressure measurements were actually carried out in a period of a few minutes.

Apparatus

The thermal conductivity of white fuming nitric acid was determined with a concentric-cylinder, steady-state type of apparatus (2) which was placed directly in a constant-temperature liquid bath. The temperature drop across the liquid layer was measured with calibrated thermistors. The temperature range of the investigation was from −47.2 to 122 F.

The dynamic viscosity of white fuming nitric acid was measured with a modified Oswald viscometer over the temperature range from −34.6 to 32 F. A Lawaczeck, or falling-cylinder, viscometer was used over the temperature range from 71.6 to 300 F. These secondary instruments were calibrated with water and carbon tetrachloride.

Specific heat measurements were made with a nonflow, bellows type of calorimeter which had been developed for use with volatile liquids. The temperature range investigated was from 32 to 80 F.

A sealed-flask pycnometer was used in a liquid constant-temperature bath to determine the density of the liquid white fuming nitric acid in the temperature range from −35 to 100 F. A pycnometer made from a selected Pyrex tube (3-mm ID, 8-mm OD, and 80 cm long) was used in an air bath for the temperature range from 100 to 300 F.

A static method was used for measuring the total pressure of white fuming nitric acid. A Smith and Menzies isoteniscope (3) was used in the temperature range from 32 to 190 F. Vapor-pressure bombs of glass, H.S. 25(L605) alloy, and stainless steel (AISI Type 347) wree used in the temperature range from 200 to 300 F.

Materials

Commercially available white fuming nitric acid with not more than 2 per cent water content was the material investigated. Solutions of the following compositions (in per cent by weight) were actually used:

HNO_3	NO_2	H_2O
97.35	1.57	1.08
94.0	5.0	1.0
99.01	0.46	0.53

The samples of acid were taken from a stainless-steel tank which contained about 100 gallons of acid. These samples were stored in two-liter glass bottles at room temperature. The composition of these samples changed due to decomposition during storage resulting from the loss of vapor when the sample bottles were opened. As vapor escaped from the heterogeneous acid systems it was observed that the weight per cent of NO_2 in the liquid phase steadily increased.

The acid compositions were determined by the back-titration of NaOH and $Ce(SO_4)_2$ (4). This standard procedure could have introduced maximum errors as great as 1 per cent in the per cent HNO_3, 3 per cent in the per cent NO_2, and 150 per cent in the per cent H_2O. This procedure did not determine the metallic compounds which were picked up by the acid from the stainless-steel storage tank. The presence of these metallic compounds may have introduced additional errors in the chemical analysis for H_2O and NO_2.

Results

The recommended thermal properties of the liquid phase of white fuming nitric acid under conditions at physical equilibrium are given in Table 1 and in Figs. 1 to 7.

In many types of heat transfer equipment the fluids are in the apparatus only a few seconds. Under these conditions the acid does not have sufficient time to decompose and approach conditions of chemical and physical equilibrium. The time required to attain physical and chemical equilibrium is about 1 hr at 200 F and about 5 min at 250 F.

Pure aluminum; H. S. 25 (L 605) alloy; Kel-F solids, greases, waxes and oils; fluorolubes; and Teflon were satisfactory materials for use with nitric acid.

Discussion of Results

Due to the decomposition of the acid, the compositions of the liquid-phase samples were unknown at the higher temperatures. All measurements were made with the liquid

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[5] Numbers in parentheses indicate References at end of paper.

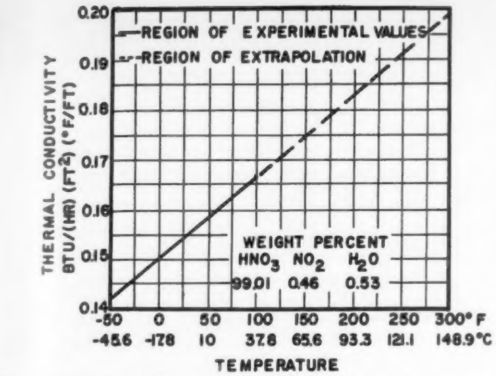

Fig. 1 Recommended values of thermal conductivity of nitric acid

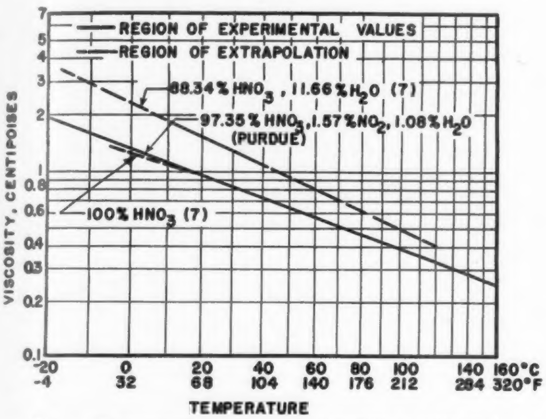

Fig. 2 Recommended values of viscosity of nitric acid

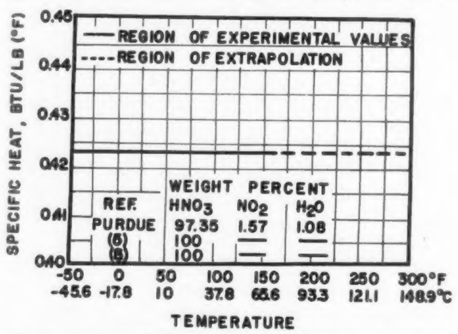

Fig. 3 Recommended values of specific heat of nitric acid

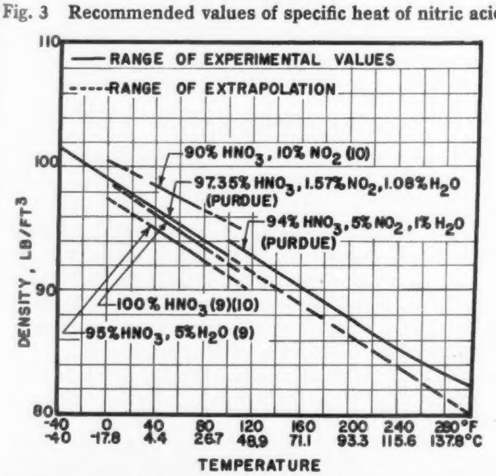

Fig. 4 Recommended values of density of nitric-acid solutions

phase in contact with the vapor phase. Measurements were made in the order of increasing temperature in order to eliminate some of the uncertainties of acid compositions. Some samples of acid which had attained chemical equilibrium at 300 F were later analyzed at room temperature. These samples contained large amounts of NO_2. However, these data were not an indication of the compositions at 300 F since all the solubilities and the partial pressures of the vapor components changed. The composition of the vapor phase was not determined.

Forsythe and Giauque (5) suggested that the net decomposition of the acid may be expressed as follows:

$$4HNO_3 = 4NO_2 + 2H_2O + O_2$$

Both the NO_2 and H_2O are highly soluble in the liquid; consequently, the decomposition continues until the equilibrium pressure is attained. The total decomposition is thus a function of the vapor-to-total volume ratio.

The errors in the thermal-conductivity values were less than 5 per cent. The maximum dispersion of the experimental measurements from the recommended values was less than 2.4 per cent over the 25 to 125 F range. This dispersion was partly due to variations in acid composition. The values reported by Van der Held and Van Drunen (6) for the dilute acid were obtained by an interesting unsteady-state method and are of the correct order of magnitude. Their values for other compounds differ as much as 14 per cent from the accepted values of thermal conductivity. Other data on solutions of NaCl, KCl, $MgCl_2$, and $CaCl_2$ show a linear temperature coefficient of thermal conductivity over a temperature range greater than 100 F, so a linear extrapolation for nitric acid (constant composition) appears to be reasonable.

The maximum errors in the viscosity measurements were of the order of 5 per cent at 300 F and less than 1 per cent at room temperature. Bingham and Stone (7) reported viscosity values in the 50 to 104 F range which are in close agreement with the Purdue measurements. Viscosity changes as great as 1 per cent were observed in a 10-hr period at 100 F; however, the chemical analysis indicated no change in composition. The acid samples were held at the high temperature only for a minimum period of time. At temperatures above 250 F the liquid phase was probably in thermodynamic equilibrium; at temperatures below 250 F the exact conditions were not known. The vapor-to-total volume ratio during the high-temperature viscosity measurements was about 5 per cent.

Most of the specific heat values were selected from those of Forsythe and Giauque (5) and Gmelin (8). The error in the recommended values was estimated to be less than 5 per cent over the entire temperature range. Reported values for pure acid at 32 F, where the composition can be accurately controlled, differ a much as 6 per cent—probably because of composition discrepancies.

The error in the density determinations was less than 0.2 per cent in the region below 100 F. At 300 F the maximum measurement error was less than 3 per cent. The vapor-to-total volume ratio during the high-temperature density measurements was about 60 per cent. The values of Veley and Manley (9) for pure acid and the values of Klemenc and Rupp (10) for pure acid and acid with nitrogen dioxide are in excellent agreement with the Purdue values in the 32 to 86 F range. Volumetric information was reported by Reamer, Corcoran, and Sage (11) for the heterogeneous, pure-acid system at equilibrium under a wide range of temperatures and pressures. Up to 220 F their bubble-point values compare quite well with the Purdue values, which were obtained with the liquid phase under similar conditions. Above 220 F the Reamer, et al., density values at the bubble point fall considerably lower than the Purdue values—about 5 per cent low at 310 F. Nitrogen dioxide additions increase the density of concentrated acid, while water additions decrease the density.

Not only the composition of the liquid phase but also the total pressure is a function of the vapor-to-total volume

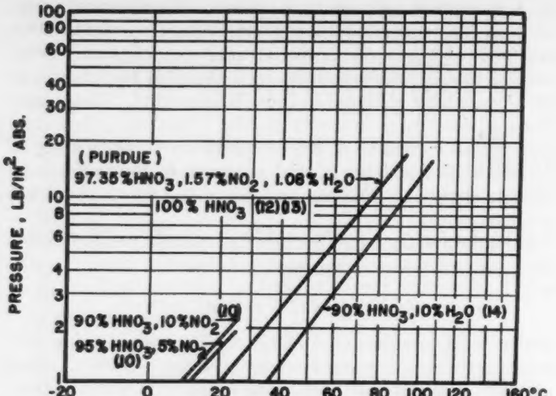

Fig. 5a Total pressure of nitric-acid solutions

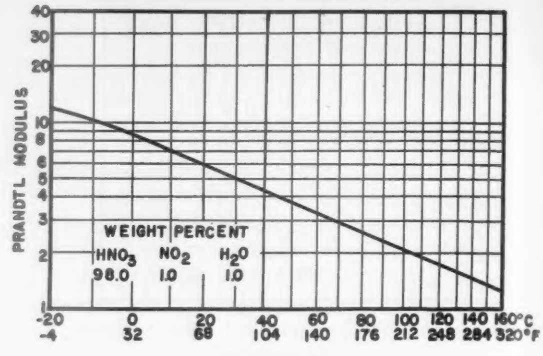

Fig. 6 Recommended values of Prandtl modulus of nitric acid

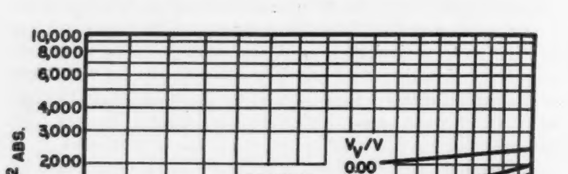

Fig. 5b Total pressure of nitric acid

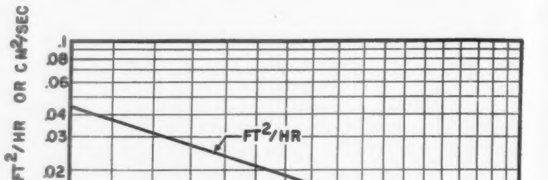

Fig. 7 Recommended values of kinematic viscosity of nitric acid

Table 1 Recommended properties of concentrated nitric acid[a]

Temperature, F	Thermal conductivity, Btu/(hr)(ft)²(F/ft)	Viscosity, centipoises	Kinematic viscosity, ft²/hr	Specific heat, Btu/(lb)(F)	Density, lb/ft³	Total pressure,[c] lb/in²., abs.	Prandtl modulus	Temperature, C
− 30	0.145	2.46	0.0590	0.423	101.0	0.023	17.35	− 34.3
0	0.150	1.73	0.0423	0.423	99.0	0.081	11.81	− 17.8
50	0.157	1.08	0.0272	0.423	96.0	0.51	7.05	10
100	0.166	0.726	0.0189	0.423	93.0	2.4	4.48	37.8
150	0.175	0.525	0.0142	0.423	89.7	7.3	3.07	65.6
200	0.183	0.397	0.0111	0.423	86.6	[b]	2.22	93.3
250	0.191	0.314	0.00912	0.423	83.4	[b]	1.68	121.1
300	0.199	0.254	0.00763	0.423	80.6	[b]	1.31	148.9

[a] Contains 95 to 97.5 per cent by weight of HNO_3 and less than 2 per cent by weight of H_2O.
[b] See Fig. 5B.
[c] Order of 25 to 50 per cent vapor-to-total volume ratio.

ratio. The total pressure data reported in Table 1 and Fig. 5a were obtained for vapor-to-total volume ratios of about 50 per cent. The error in these measurements varied from less than 10 per cent at 32 F to less than 0.3 per cent at 176 F. Values reported by Egan (12), Klemenc and Rupp (10), and Wilson and Miles (13) are in good agreement with the Purdue values, while those reported by Taylor (14) are somewhat lower in the low temperature region.

In Fig. 5b are presented the equilibrium pressures reported by Reamer, et al. (15) for pure nitric acid at low vapor-to-total volume ratios. These data were reported to be accurate within 2 psi or 0.2 per cent, whichever is greater. Measurements made at Purdue, in glass apparatus, are in qualitative agreement with these data. At Purdue, higher total pressures were observed in glass apparatus than in metal apparatus for the same vapor-to-total volume ratio. Presumably these differences resulted when oxygen from the decomposition products reacted with the metal container.

More detailed information concerning the effects of H_2O and NO_2 contents on the thermal properties of nitric acid has been compiled in another report (16). In general, NO_2 additions and H_2O additions have opposing effects on the thermal properties.

(*Continued on page 180*)

Technical Notes

A Remotely Controlled Aerial Torpedo[1]

An anonymous article of historical interest translated from *Deutsche Luftfahrer Zeitschrift*, January 22, 1918, pages 22–23

Contributor's Note: **The history of our field is filled with fascinating anticipations. Here we have a pulsejet surface-to-surface missile, complete with guidance system, and assisted take-off—all vintage 1918! Unfortunately, the inventor is unknown.**

IN THE daily press and in Army reports we frequently read about aerial torpedos. This nomenclature probably designates nothing more than a large torpedo-shaped droppable mine. An aerial torpedo which would really be useful for defense against airships, etc., must be driven by a strong, light engine, must be capable of flight through the air at high speed, and must be capable of being steered in any direction from the ground by means of electromagnetic waves.

The torpedo consists basically of a 6-meter long tube of sheet aluminum (Fig. 1) having a highly polished exterior surface and comprised of the following parts: an ogival head A; a cylindrical section B, 350 mm in diameter, having two small wings R; a conical extension C, D, E, and F; and a tail G carrying vertical and horizontal stabilizers and elevator and rudder. The weight of the entire tube (without motor and installations) is considered by the inventor to be approximately 12 kg.

The engine (Fig. 2) is located in section B of the tube. It has 8 cylinders of 120-mm diam and an 80-mm stroke and runs at 1500 rpm. The exhaust cams are so designed that the exhaust valves open immediately after ignition and explosion of the gas mixture. The combustion gases, which are at very high pressure, are emitted to the atmosphere without doing much work in the cylinders through exhaust pipes tipped with specially shaped nozzles (at e, Fig. 1), thus driving the torpedo at high speed by reaction.

Since the engine works at low compression and its components, such as piston rods, crankshaft, etc., are not used to transmit strong forces, all parts can be kept very light. It is assumed that the weight of the engine in the projectile will be only 35 kg. The air necessary to form the explosive mixture enters through intake openings at a (Fig. 1). The engine is cooled by air which enters at a, passes over the cylinders, and exits at v. Air cooling is very effective due to the speed of the torpedo.

The stability of the missile is assured both by its stabilizing surfaces and its intrinsic speed.

Electrical steering mechanisms are provided to maintain the missile's flight at a predetermined altitude and to permit its lateral control.

The engine drives (Fig. 3) a small dynamo D through a gear take-off. The dynamo provides current not only for the engine's ignition and the missile's electrical control, but also for signal lights F, F_2, which make it possible to observe the torpedo at night and control its steering. The tail end of the torpedo (Fig. 3) carries the elevator G, and rudder G_2; both controls are activated by electromagnets. The elevator G_1 is controlled by an aneroid barometer B which acts upon a switch C in such a manner that if any change occurs relative to the preset altitude (or atmospheric pressure) at which the

Received January 21, 1954.

[1] Contributed by George Chernowitz, Director, American Power Jet Company, Ridgefield, N. J.

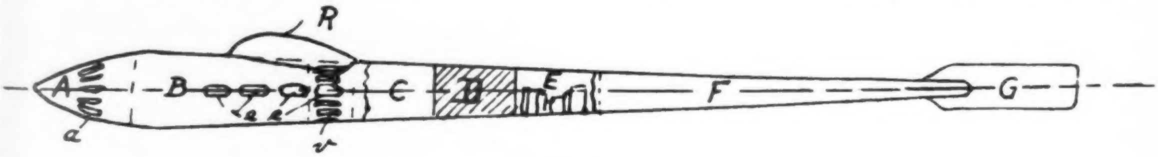

Fig. 1

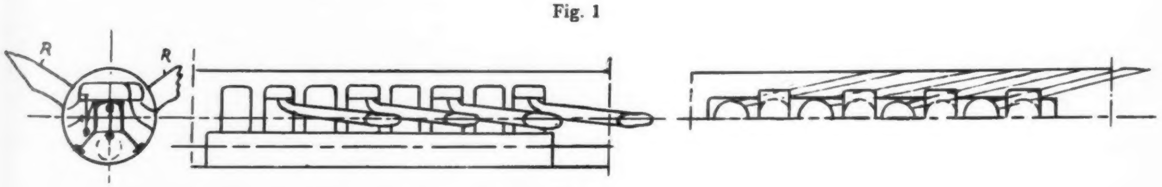

Fig. 2

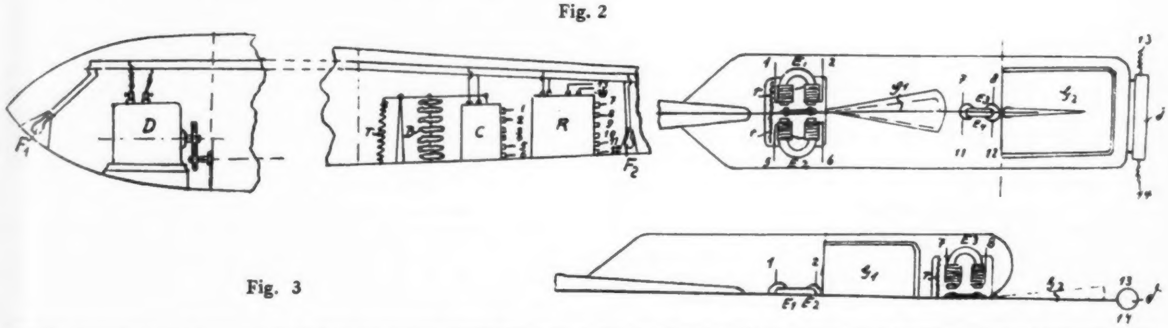

Fig. 3

EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see first page of this issue).

Type of vehicle	Weight of vehicle ready for use	No. of passengers at 70 kg per	Total weight, lb	Engine power, PS	Speed on level — ground — m/sec	km/h	Efficiency of the vehicle	Required tractional force on level ground, kg	Tractional coefficient
Town car	1000	3	1210	12	10	36	0.60	$0.6 \times \frac{12 \times 75}{10} = 54$	$\frac{54}{1210} = 0.044$
Touring car	1700	4	1980	50	22	80	0.60	$0.6 \times \frac{50 \times 75}{22} = 102$	$\frac{102}{1980} = 0.051$
Racing car	1200	2	1340	100	45	162	0.60	$0.6 \times \frac{100 \times 75}{45} = 100$	$\frac{100}{1340} = 0.074$

Table 1

torpedo is to fly, one or the other of the two electromagnets E_1 or E_2 pulls the elevator in the desired direction until the torpedo is at the proper altitude. Contacts 1 and 2 act on magnet E_1; contacts 5 and 6 on E_2; and when the barometer needle is on contacts 3 and 4, the current to the magnets is cut off and the elevator G_1 is drawn back to its neutral, horizontal position by one of the springs r. By means of this ingenious device, the torpedo is enabled to maintain any desired, predetermined altitude.

The lateral steering of the torpedo is controlled by radio signals from a transmitter on the ground. The signals are sent to a well-insulated receiver d in the tail of the torpedo. Receiver d is connected by lines 13 and 14 to relay R, which is installed in a line tapped from the dynamo with interposed resistances. In the relay box, there is a distributor with several contacts, of which 7 and 8 activate electromagnet E_3 pulling G_2 to the right, and 11 and 12 activate E_4 pulling G_2 to the left. When distributor R is on contacts 9 and 10, E_3 and E_4 are cut off and G_2 goes to neutral position, pulled by one of the springs r.

Naturally, the torpedo is only controllable within range of sight (i.e., within several kilometers of the operator). The weight of the steering apparatus with dynamo, electromagnets contact apparatus, distributors, relays, etc., is estimated by the inventor at approximately 10 kg. In addition, the torpedo requires approximately 10 kg of gasoline and oil in chamber C (Fig. 1), which is near the center of gravity of the torpedo, in order to moderate the effect of the continuous decrease in the weight of the fuel during flight. The explosive charge is located in chamber D. The total weight of the torpedo ready for action is comprised of the following:

Body of torpedo with wings and tail surfaces	12 kg
Reaction engine	35
Control apparatus, etc	10
Fuel and oil	10
Explosives	10
Approximately	77 kg

The reaction engine does not have the power to provide an initial acceleration adequate to lift the torpedo from the ground, so that a mechanical launching device is necessary. However, the engine is said to be powerful enough to maintain the torpedo in flight at high speed, as may be ascertained from the following calculations by the inventor.

The inventor bases his calculations on the so-called tractional coefficients of motor vehicles as determined by experiment. They are summarized in Table 1.

In view of the fact that, at high speeds, the greater part of the power of a motor vehicle is expended in overcoming the resistance of the air, the inventor finds by interpolation that the tractional coefficients for the aerial torpedo are 0.10, which conform with the results of the inventor's experiments. The trational force necessary to maintain flight is thus 80 kg $\times$ 0.10 = 8 kg.

An engine of the above dimensions has a total cylinder volume of 7.2 liters, and at 1500 rpm has an intake of twelve times this volume per second, i.e., $12 \times 7 = 84$ liters of air-gas mixture. This 84-liter mixture represents a mass of $(84 \times 1.293)/\times 9.8 = 11$ gm, which is emitted at a speed of 800 m/sec. (The figure 1.293 is the density of air at 0 C and 76 mm, which would not be correct here. However, the exhaust gases contain a large quantity of carbon dioxide which is heavier than air, so that this is compensated for.) The motor thus delivers $0.011 \times 800 = 8$ kg tractional force. A favorable factor is that the engine takes in air from the front through openings a (Fig. 1), which to a certain extent creates an area of reduced pressure in front of the tip of the torpedo. Another favorable factor is that at the high intrinsic speed of the torpedo, the emissions of the individual cylinders do not interfere with each other, but rather that each acts individually on a separate air cushion and drives the torpedo forward.

Even if many assumptions, etc., in this calculation appear to be somewhat arbitrary, nevertheless we would rather not assign this interesting project with no further ado to the realm of the impossible; in the final analysis its realization is only a question of time.

Interaction Between Pressure Waves and Flame Fronts[1]

G. H. MARKSTEIN[2] and D. SCHWARTZ[3]

Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y.

Introduction

THE combustion process in jet and rocket engines occurs under flow conditions characterized not only by a high level of random eddy motion ("turbulence") but also by the presence of intense sound waves that may include random "noise" as well as resonance oscillations of various types. A third mode of disturbance, "entropy spottiness" (1),[4] may also be of considerable importance within the burning zone and farther downstream. Our present knowledge about the coupling phenomena between these disturbance fields and the combustion process is extremely rudimentary. For the purpose of unraveling these complex interactions, investigations of the effects of a single type of disturbance on flame propagation would seem indispensable. This approach has indeed

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[1] This research was conducted under the auspices of Project SQUID, jointly sponsored by the Office of Naval Research, Department of the Navy, Office of Scientific Research, Department of the Air Force, and Office of Ordnance Research, Department of the Army.

[2] Head, Combustion Section, Aerodynamic Research Department.

[3] Physicist, Combustion Section, Aerodynamic Research Department.

[4] Numbers in parentheses indicate References at end of paper.

been employed in various recent studies of turbulent flames, but has not yet been applied systematically to the equally important effects of pressure waves on combustion.

Apparatus and Procedure

In the work described in this preliminary note, the shock tube technique was chosen as a convenient means for subjecting a flame front to controlled pressure wave disturbances. The apparatus is shown schematically in Fig. 1. The shock

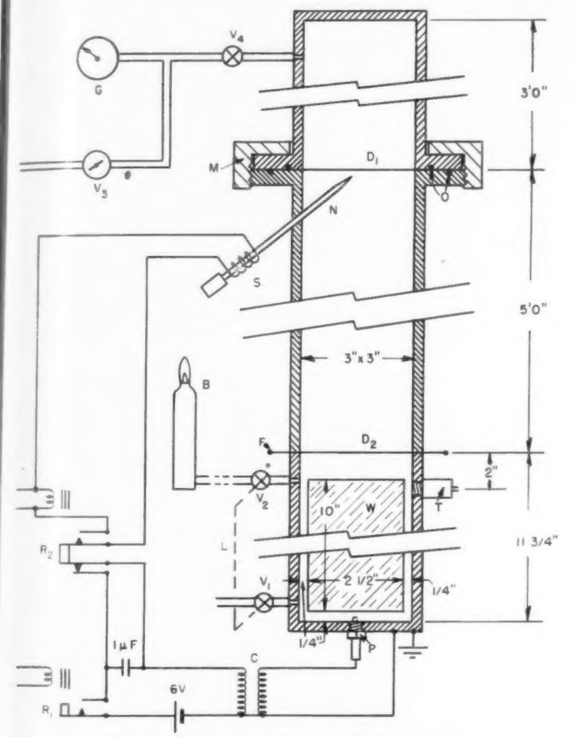

Fig. 1 Schematic diagram of apparatus

tube, of the indicated dimensions, has a square cross section and consists of a high-pressure chamber, a central portion, and a combustion chamber. It was mounted vertically in order to minimize buoyancy effects that are known to cause appreciable asymmetric distortions of flames propagating in horizontal tubes.

Preceding each experiment, the high-pressure chamber was sealed against the central portion by a diaphragm D_1 made from photographic film stock, which was clamped between "O" rings O by means of the threaded ring M. Compressed air was admitted to the chamber through the regulator valve V_3 and needle valve V_4. A chamber pressure of 25 psig, measured by the precision gage G, was used in the present work. With the air in the central portion remaining at atmospheric pressure, this corresponds to a shock pressure ratio of about 1.6. The combustion chamber was separated from the central portion by a thin membrane D_2, prepared previously by pouring "Tester's Microfilm" on water, lifting the film off with a wire frame F and letting it dry. Air and gaseous fuel were mixed in desired proportion in a flow system provided with rotameters, passed through the combustion chamber through valves V_1, V_2 and into a nozzle burner B. The appearance of the burner flame provided a rough check on attainment of proper composition of the combustible mixture. After flushing the combustion chamber for several minutes, the inlet and outflow valves V_1, V_2 were closed in rapid succession by the linkage L, leaving the chamber filled with mixture at atmospheric pressure.

The interaction phenomenon was studied by taking high-speed schlieren motion pictures through flush-mounted glass windows W and by recording pressure transients with the condenser-type transducer T. Timing traces on the movies and on the oscillographic records were obtained by means of a 2500 cps crystal oscillator. A "Goose" timing device was used for controlling the "Fastax" camera, the oscillographic recording camera, and the relays R_1 and R_2. Relay R_1 served merely for starting the current through the primary winding of ignition coil C at the beginning of the Goose cycle. After a delay sufficient for bringing the cameras up to speed relay R_2 was closed by the "Event" timer of the Goose. A reproducible delay of suitable magnitude between ignition of the combustible mixture by spark plug P and rupture of diaghragm D_1 was achieved by using a pair of normally closed contacts of R_2 as ignition breaker points and a pair of normally open contacts of R_2 for energizing the solenoid S that actuated the diaphragm-piercing needle N.

Preliminary Results and Discussion

The upper trace of Fig. 2 is a pressure record obtained with air in the combustion chamber and shows the consecutive arrival at the transducer of the primary shock wave, the shock wave reflected from the bottom of the combustion chamber, and the expansion wave reflected from the top of the high-pressure chamber. Thereafter the pressure transient is seen to repeat by reflection at the closed ends, decaying gradually without appreciable change of wave shape. The lower trace of Fig. 2 shows a pressure record obtained with the same initial

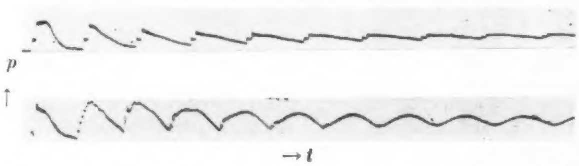

Fig. 2 Oscillographic records of pressure transients in the shock tube

Top: without combustion; *bottom:* with combustion in stoichiometric butane-air mixture.

shock strength while a stoichiometric n-butane-air mixture burned in the combustion chamber. Comparison with the upper trace reveals the following new features: a weak expansion wave arrives before the reflected shock wave, owing to reflection of the primary wave at the flame front; the reflected shock wave is stronger than without combustion; and it is followed immediately by an expansion wave that must have its origin in the interaction since it arrives before the expansion wave coming from the top of the high-pressure chamber. In the following cycles the original shock wave breaks up into several weak shocks, owing to multiple reflections at the flame front or the burned gas-air interface as well as at the closed ends. This results in the gradual change of the recurrent transient into an attenuated pressure oscillation of smooth wave shape.

The pressure records taken thus far have not yet been evaluated in detail. It is planned to take simultaneous records with two transducers placed upstream and downstream of the flame front and evaluate them in terms of boundary conditions at the flame front. Lack of information on these boundary conditions has been a major cause of uncertainty in the application of the wave diagram method (2) to combustion phenomena.

The frame rate of the Fastax camera, about 6700 frames/sec, was not high enough for resolving the initial phases of the interaction or for making the shock waves visible. For this reason, the motion picture studies will be supplemented by spark photography in future work. The development of a highly distorted flame shape subsequent to the initial phase could be well observed, however, on the movies. A sequence of frames selected from a schlieren movie of flame-front pres-

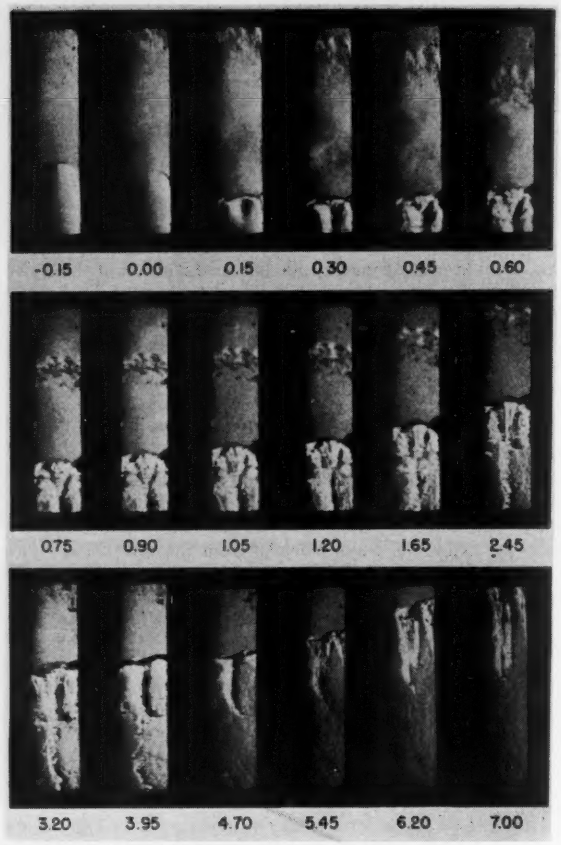

Fig. 3 Schlieren high-speed motion picture of pressure wave-flame front interaction

Numbers below frames denote time in milliseconds from instant when primary shock reaches flame front.

sure-wave interactions in a stoichiometric n-butane-air mixture is shown in Fig. 3. The first frame shows the appearance of the flame front about 20 msec after ignition and 0.15 msec before the shock wave reached it. Owing to insufficient time resolution, the next frame shows merely a blurred outline of the flame at the beginning of interaction. The following frame indicates that passage of the primary shock has left the flame indented in the center toward the burned gas, but has not caused roughening or breakup of the flame surface. Beginning with the next frame, the flame gradually assumes an elongated funnel-shape and its surface acquires a granular appearance. Comparison with the pressure record shows that this phenomenon is initiated by passage of the reflected shock wave through the flame. Finally, coinciding with arrival of the expansion wave at the flame front, a further breakup of the latter into several funnels takes place, as seen on the last three frames.

These phenomena seem compatible with the results of analyses of contact surface (3) and flame front (4) stability in accelerating flow. According to these theories, acceleration directed toward the denser medium should cause instability and acceleration in the opposite direction stability of the front. In this interpretation, the primary shock wave does not create a major distortion because it accelerates the flame toward the burned gas. Both the reflected shock wave and the expansion wave, however, accelerate the flame toward the unburned gas, and the resulting instability is the cause of the drawn-out funnel shape. Similar deeply penetrating distortions of contact surfaces accelerated toward the denser medium have indeed been observed (5, 6). It must be emphasized, however, that the stability analyses (3, 4) apply strictly only to constant acceleration. In particular, the impulsive acceleration of very short duration that takes place during passage of a shock wave need not necessarily have the effects predicted by these theories. In order to clarify these matters further, the work will be extended to other conditions of interaction, such as reversed direction of flame travel or initial interaction with an expansion wave, and the influence of combustible mixture composition and of shock strength will be systematically explored.

Acknowledgment

The authors are grateful for valuable contributions to this work by Messrs. J. G. Logan, Jr., and L. M. Somers.

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Ullage Requirements in Tanks

DARELL B. HARMON, JR.[1]

College of Engineering, University of California at Los Angeles

Two formulas are found for the required ullage fraction in a sealed tank containing liquid for given predetermined values of allowable tank pressure and temperature of storage. The perfect gas law is assumed to hold for the gas in the tank, and solubility of the gases in the liquid is ignored.

IT IS desired to find a formula that is simple to use for predetermining the necessary fraction of a tank volume that must be left empty when the tank is filled in order to assure safety from rupture of the tank when sealed. The ullage left in a filled sealed tank can be very important if the tank is stored under adverse conditions or if a maximum of liquid is desired in the tank such as in a liquid propellant rocket. In the latter case, space and weight are at a premium so that greatest possible efficiency in the use of the tank is required consistent with the conditions which the tank may meet in storage. In other storage cases it may be desirable to find the minimum suitable ullage to reduce shipping costs, etc.

The factors which influence the choice of the ullage fraction of the tank volume are the liquid specific weight W, and vapor pressure P_v, the maximum temperature which the tank may reasonably be expected to reach (T_M), the ordinary filling temperature T, the tank material coefficient of expansion (a), the filling pressure P_1, and the allowable pressure in the tanks P_f. It will be assumed that any gas in the tank after filling can be treated as a perfect gas. The solubility of this gas in the liquid in the tank is of importance too, but usually the common gases such as air or some of the inert gases are negligibly soluble in the ordinarily stored liquids at the al-

(*Continued on page 180*)

Received January 10, 1955.

[1] Assistant Professor.

Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*

Jet Aircraft, Engines

VOODOO, the F-101, is a new USAF supersonic, long-range strategic fighter built by McDonnell. Two P&W J-57 turbojets power the craft, which is capable of carrying atomic weapons.

A speed of over Mach 1 was recently reported for the Convair F-102 jet interceptor in level flight at 30,000 ft. The F-102 is powered by a newly modified J-57 turbojet with afterburner to provide 16,000 lb thrust. The plane is equipped with a new nose and canopy and is sporting tail blisters to eliminate supersonic buffeting.

Flight tests of the new B-66 twin-jet bomber are now being conducted at Edwards AFB, Calif. The bomber, powered by Allison J-71 turbojets, can fly at speeds of 600–700 mph and can operate at altitudes up to 45,000 ft. Specifications: span, 72 ft 6 in; length, 75 ft; height, 23 ft 7 in.

USAF has awarded Ryan Aeronautical Company, San Diego, Calif., a contract for the development of a jet-powered VTO aircraft. No other details were announced.

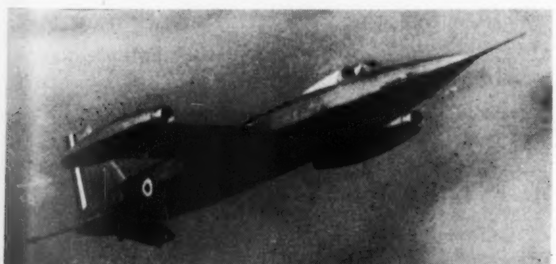
Designated as the L-1449, Lockheed Aircraft has released information on its proposed turboprop liner. Featuring thin wings and mounting four P&W PT-2 turboprop engines of 6000 eshp each, the liner promises to carry 17,400 lb (60–80 passengers) at a crusing speed of 430 mph. Maximum loaded weight is about 177,000 lb.

The Convair 340 is to be equipped with the new Napier-Eland turboprop engine for demonstration to airline operators.

The Douglas DC-8 jet liner is expected to be delivered to United Airlines late in 1959 for passenger use. Sweptwing DC-8 is to be powered by four P&W J-57 turbojets.

According to the Atomic Energy Authority of Britain, the atomic engine for aircraft will probably be a turbojet-type power plant. The authority stated that the solution of enabling metals to withstand high levels of temperature and radioactivity is close. However, it was pointed out that the chief problem is to develop a power plant small enough to propel itself. It was stated that such a plane could be flying in 10–15 years and may be in the form of a flying boat weighing some 150–200 tons fully loaded.

The SNCASO S.O. 9000 combines turbojet and rocket in this novel French fighter (photo). The plane has two turbojets

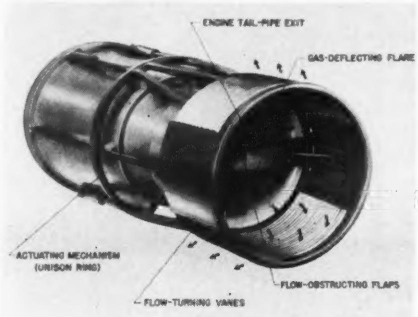


of 880-lb thrust each at the wingtips for normal operations. A SEPR rocket is located in the tail and is used for high-speed bursts.

The Leduc 021 ramjet aircraft recently set a speed record of 652 mph while in a 50-deg climb. Development tests are still under way in France.

The Caravelle, SE-210, the new French SNCASE jet transport, is rapidly nearing completion. Tests are expected to begin this summer.

Further details have been released specially to JET PROPULSION concerning the Aerojet-SNECMA thrust reverser. The



AEROJET-SNECMA THRUST REVERSER

exhaust jet leaving the nozzle of the engine tail pipe is surrounded by a bell-mouthed deflecting flare. When the reverser is actuated, a portion of the exit area is obstructed by flaps, causing an outward flow following the contour of the flare. The gas stream is deflected outward so that it is caught, and the direction of flow is reversed, by the turning vanes located directly downstream of the deflecting flare exit. When not in use, the turning vanes are retracted into the engine nacelle and the exhaust jet is unobstructed. In this condition, no thrust loss is experienced. The partial obstruction of the exhaust gas stream may also be accomplished by injecting compressor bleed-air at the exit of the deflecting flare.

The French firm of SNECMA has patented a combination ramjet-turbojet engine. Oblong ramjets are located in the wings, and a bleed from the turbojet compressor feeds air to the ramjet during low-speed flight such as at take-off. The air to the ramjet can be varied according to the speed of the aircraft.

A 10 per cent increase in thrust over the J47-GE-17 turbojet is expected with the new J47-GE-33 in F-86D installations. New features include ceramic coated afterburners, electronic engine controls, new afterburner ignition system, new compressor vane angle, and enlarged air ducts.

Starts for jet engines are to be more versatile and less expensive with the new jeep-mounted AiResearch gas turbine engine. Push button, fully automatic operation will also enable the unit to cool or heat the interior of planes, supply power, or melt ice.

The Rolls Royce Soar turbojet engine is slated for installation in a USAF target drone. Soar, of axial flow design, weighs only 267 lb and delivers 1810-lb thrust.

Figures have been released giving performance data of afterburner operation in the de Havilland Vampire jet. Thrust was upped 25 per cent and enabled the aircraft to attain an altitude of 50,000 ft. Chief disadvantage was the large increase in fuel consumption. A jet engine delivering 17,000-lb thrust increases its fuel flow from 2060 gph to 6360 gph. For operation at sea level and at speeds of Mach 1.5, the fuel consumption would be 10,000 gph. Turbo-driven centrifugal pumps are being developed in Britain to increase flow rates over normal fuel pumps which are presently being taxed beyond capacity.

EDITOR'S NOTE: **The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.**

Research and Facilities

NORTHWESTERN University is expanding its Gas Dynamics Laboratory for work on gas turbines, jet propulsion, and rockets. A new program is to be concerned with combustion instability of rocket motors.

General Electric Co. has acquired a 4500 acre tract near Peebles, Ohio, for construction of an advanced outdoor testing site for jet engines and related components. The new facility will supplement its Evendale, Ohio, testing operations. The large \$$1/4$ million site is needed for testing jet engines for VTO and reverse thrust applications.

The Ramo-Wooldridge Corp. of Los Angeles, Calif., and Westinghouse are to be engaged in a million dollar program to develop airborne miniaturized computers for high-speed, tactical jet aircraft, and guided missiles.

Increased use of reinforced plastics in guided missiles is seen as the Guided Missiles Div. of the Fairchild Engine & Aviation Corp., Wyandanch, N. Y., expands its plastics facility. Plastics items include missile radomes, control surfaces, wing tips, fairings, pressure vessels, and light armament.

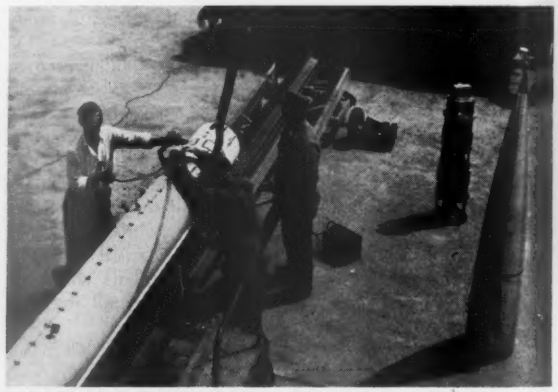
Westinghouse Electric Corp. will invest \$19.5 million to expand and improve its Aircraft Gas Turbine facility at Kansas City. All of its gas turbine production is to be concentrated here, with a new jet engine flight test center at Olathe, Kan., 20 miles away.

Completed at Cornell Aeronautical Laboratory, Buffalo, N. Y., is a new \$600,000 continuous-flow wind tunnel capable of a speed range of Mach 0.8–2.8. With a test section of one square foot, the tunnel features vertical return and variable density, is 46 ft long, 15 ft high, and weighs about 20 tons. Power is from a 2600 hp motor. A perforated wall ventilates the test section to eliminate choking. Shakedown runs are now being made.

A Visit to Holloman Air Development Center

HOLLOMAN Air Development Center in southern New Mexico operates as a part of the USAF Air Research and Development Command to test pilotless aircraft, guided missiles, and related aircraft. The center, formerly known as Alamogordo Army Air Field, was begun in 1942. In the northwest corner of the center, the first atomic explosion took place on July 16, 1945. The first rocket was launched there in September, 1947. Recently the Holloman range and the range of the Ordnance Base at White Sands were consolidated into an integrated range shared by the Army, Navy, and the Air Force. Holloman also conducts research and development in space biology, and supports research programs in guided missiles, electronics, and atmospherics, as well as physiology and psychology. Additionally, it provides facilities for contractors and other government agencies to conduct research and development operations. Shown here are some of the varied unclassified activities being conducted at Holloman.

GETTING READY . . . Lt. Col. John Stapp, Chief of the Aero Medical Lab. and ARS Member, is strapped into the rocket sled. He has been subjected to speeds of over 600 mph and forces of 35 g's.



ELECTRONIC CHECK OUT . . . Hours of careful checking take place before a rocket such as the Aerobee shown here is fired. At right is the nose cone which covers the instrument section seen in the background.

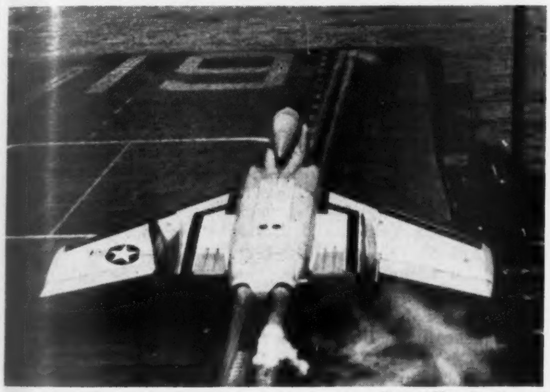
PAYLOAD PLACED IN AEROBEE . . . Section carries instruments used for upper air research. This section is recovered by paarchute for examination and possible reuse.

FUELING BEGINS . . . . Protective Clothing is worn by crew. In the foreground is the solid propellant booster used to accelerate the Aerobee.

News in Pictures

North American

GOING UP . . . JATO bottle mounted on wingtip of aircraft is pointed upward to study effect of rocket as a spin recovery aid. Tests were conducted by North American Aviation in cooperation with USAF. Motor delivers 800-lb thrust for 6.55 sec.

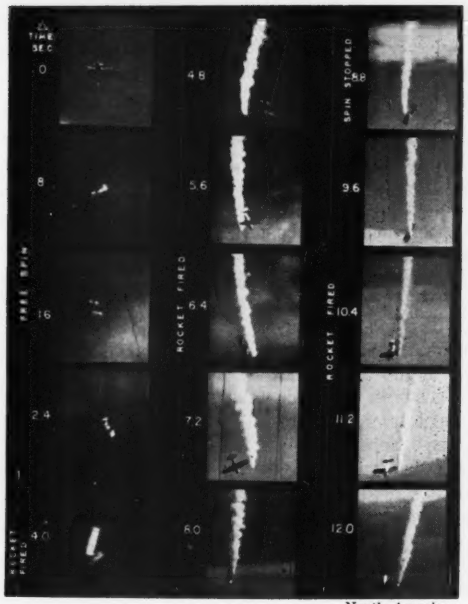


Chance Vought Aircraft

GOING UP . . . Afterburners ablaze, F7U-3 is also boosted by steam catapult aboard U.S.S. Hancock.

Martin Aircraft

GOING UP . . . Viking 12's attempt at single-stage altitude record is "close but no cigar." It reached 144 miles, 14 miles under Viking 11's record. Its assignment: study thermal barrier and ionosphere.

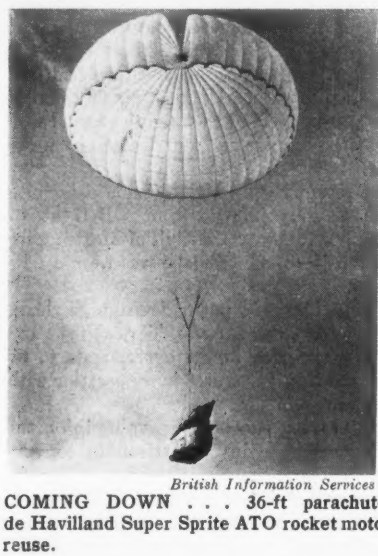


North American

COMING DOWN . . . Plane in right spin (left frame) recovers when rocket mounted on left wing tip (thrust aft) is fired (bottom left and center). Recovery is complete in about 4 sec (right frame).

British Information Services

COMING DOWN . . . New British carrier fighter twin jet de Havilland 110 comes for landing on angled deck of H.M.S. Albion.



British Information Services

COMING DOWN . . . 36-ft parachute brings expended de Havilland Super Sprite ATO rocket motor back to ground for reuse.

Instruments and Materials

DYNAMIC Instrument Company, Cambridge, Mass., has designed a water-cooled adapter for standard pressure transducers to permit operation at temperatures up to 4000 F.

Kennametal, Inc., Latrobe, Pa., has developed sintered titanium carbide for use at temperatures up to 900 F. Eventual operation is aimed at over 2000 F.

A sound spectrometer has been invented by a British firm for measuring the noise of jet engines. The sound is translated into visible form and is projected onto a screen in a series of vertical lines, each proportional in height to the amplitude of its component.

Scientists at Armour Research Foundation have developed an electrical, liquid oxygen, level gage for high-altitude aircraft oxygen systems. Present models, weighing less than 2 lb, can withstand a differential pressure of 20 psi with a full-scale range as low as 0.15 psi in a 5-liter converter tank.

The Wisconsin Centrifugal Foundry of Waukesha, Wisc., has successfully produced centrifugal castings of titanium. thus overcoming present titanium casting difficulties.

Tubing can be created from sheet copper, aluminum, and steel in a new process developed by Olin Mathieson Corp., East Alton, Ill.

A jet blast cooling and quieting device has been patented by Reaction Motors, Inc.

It is predicted that the jet transport of 1970 will incorporate a double fuselage of about 8 in. thick to reduce noise.

Britain has successfully employed asbestos-filled plastics in rocket nozzles, illustrating their good thermal properties. Glass fiber has also been used in combination with asbestos. In other quarters, rocket motors for such missiles as Nike are reported to be using graphite, silicon carbide, and zirconium Meanwhile Marquardt Aircraft Co., Van Nuys, Calif., has said that present operating temperatures in uncooled afterburners and ramjets are within 200–300 F of the melting points of our best high temperature alloys. New alloys utilizing chromium, rhenium, silicon, and vanadium appear to be nearing the reach of industry within a few years. Meanwhile, molybdenum, ceramic coatings, and cermets are expected to fill immediate needs. New material developments are claimed to be necessary to enable increasing performance of power plants by raising operating temperatures.

Miscellaneous

Future jet aircraft will be protected with explosion and fire suppression systems installed in fuel tanks and other vital parts.

Two US heavy naval cruisers, the *Boston* and *Canberra*, are to be outfitted as our first operational guided missile ships.

The sound intensity from a F-100 jet fighter may be as high as 160 decibels at the tailpipe and 120 decibels at a distance of 1000 ft.

Two Air Force men recently set a high-altitude parachute record when they successfully jumped from a B-47 at an altitude of 45,000 ft. Bailouts over the Gulf of Mexico were made at a temperature of −37 C. Escape was from a new downward ejection seat.

New cosmic ray soundings will be made from Skyhook balloons at Goodfellow AFB, San Angelo, Tex. Up to 150 lb of instruments will be carried in the experiments to be conducted by the Office of Naval Research in cooperation with the Atomic Energy Commission.

Cast magnesium outer wing panels will save 67 lb on the Chance Vought Regulus missile in comparison to conventional sheet-metal construction.

Silicone resins reinforced by glass fiber are to be used in the radomes of jet bombers where the skin temperature may reach 400 F.

Commercial Properties of White Fuming Nitric Acid

(*Continued from page 172*)

Acknowledgments

This investigation was supported by the National Advisory Committee for Aeronautics. Special thanks are due Professors M. Zucrow, C. E. Warner, and J. E. Brock for their aid in all phases of this investigation.

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Ullage Requirements in Tanks

(*Continued from page 176*)

lowed tank pressures and temperatures. For that reason, dissolving of the gas in the liquid in the tank will be disregarded. Then the calculations made here will have an automatic factor of safety in them. The tank material is considered to be inert with respect to the filling liquid.

The ullage fraction U, ratio of volume left empty to total

tank volume, can then be found from the previously mentioned factors. The subscripts 1 and 2 will be used to indicate initial and final conditions.

Three cases are considered. The simplest is that in which there is no air or other gas in the tank after filling, but only vapor from the liquid put in the tank. The pressure in the tank at the expected maximum temperature is then the vapor pressure at this temperature provided the liquid does not expand to completely fill the ullage. To prevent excessive pressures in the tank it is only necessary to set the ullage greater than the expected liquid expansion. Then, since the total liquid weight is constant, the *minimum* ullage fraction is found from

$$W_1[1 - U] = W_2[1 + a(T_M - T)]^3 \quad \text{........[1]}$$

Therefore the fraction is

$$U = 1 - \frac{W_2}{W_1}[1 + a(T_M - T)]^3 \quad \text{..........[2]}$$

In the second case the vapor pressure of the liquid is initially negligible so that air or some other gas fills the ullage. The final pressure then determines the required ullage

$$P_f = P_{v2_t} + P_{2(\text{gas})} \quad \text{................[3]}$$

in which the final gas pressure is found from the perfect gas law utilizing the change of volume of the tank, and the change of specific weight of the liquid stored. Then

$$P_{2(\text{gas})} = P_1\left(\frac{T_M}{T}\right)\left(\frac{U}{[1 + a(T_M - T)]^3 - \dfrac{W_1}{W_2} + U\dfrac{W_1}{W_2}}\right) \quad \text{..........[4]}$$

in which the last factor is simply the ratio of the initial gas volume divided by the final gas volume. Substituting Eq. (4) in Equation [3] and solving for the desired ullage fraction,

$$U = \frac{\left(\dfrac{P_f - P_{v2}}{P_1}\right)\dfrac{T}{T_M}\left\{[1 + a(T_M - T)]^3 - \dfrac{W_1}{W_2}\right\}}{1 - \dfrac{W_1}{W_2}\left(\dfrac{P_f - P_{v2}}{P_1}\right)\dfrac{T}{T_M}} \quad \text{....[5]}$$

The third case arises when the initial vapor pressure of the liquid is not negligible. The initial pressure of the gas in the tank is then usually atmospheric pressure minus the liquid vapor pressure. With this substitution, Equation [5] is applicable to the third case.

As an example, the pressure rise of water in a tank is plotted vs. chosen ullage fraction in Fig. 1 for various final temperatures when the filling temperature is 60 deg F. The tank was taken to be aluminum. The very rapid rise of pressure ratio can be noted from the figure as the ullage fraction is decreased toward that which will give no leftover volume for the air after allowing for the expansion of the liquid.

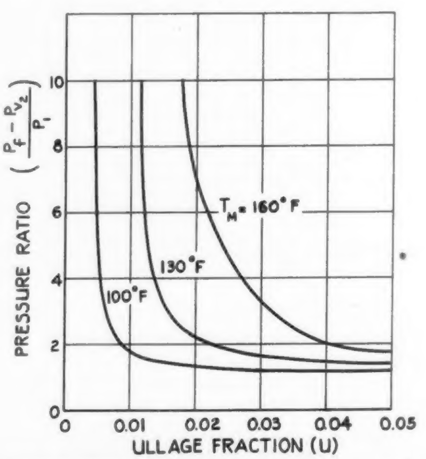

Fig. 1. Gas pressure rise vs. ullage fraction in a water-filled aluminum tank for three storage temperatures. Filling temperature is 60 deg F

In this paper the tank expansion under pressure was ignored as was the compressibility of the liquid and the absorption of the gas over the liquid by the liquid. One other factor is of great importance in cases in which tank sizes may vary. It can happen that tank size tolerances become an appreciable part of the ullage fraction. In these cases it is important to fill the tanks so the ullage fraction is correct in the smallest possible tank size, otherwise tank ruptures may occur.

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ARS News

Baltimore Program Complete

Pendray to speak at ARS luncheon; Martin Aircraft to stage program

DETAILS have been completed for the ARS 25th Anniversary Meeting to be held April 20–22 in Baltimore, in conjunction with ASME's 75th Anniversary affair, April 18–22.

ARS registration will be at both the Lord Baltimore and Southern Hotels, although all the ARS sessions and functions will be at the Southern. Programs have been mailed to all members, including reservation forms for feature events.

G. Edward Pendray, main speaker for the ARS luncheon on April 20, will talk on "Twenty-Five Years of Rocketry." A founder and former president of the Society, Dr. Pendray is the donor of the G. Edward Pendray Award for contributions to literature in the rocket and jet propulsion field. Toastmaster for the event will be president Richard W. Porter.

Sears Williams, vice-president of the Baltimore Section and chairman of the meeting, announces that The Glenn L. Martin Co. will be host to a gratis dinner in the Calvert Room of the Lord Baltimore on April 20. Speaker will be Martin vice-president E. G. Uhl, and his subject is "The Engineer and the Aviation Industry." A Matador display will be set up in the hotel ballroom.

Distinguished representatives of government and industry are expected to participate in the ASME panels to be held during the week. First panel, on "The Engineer's Responsibilities in Government," is on Tuesday afternoon, April 19. The second, on "The Engineer and the Prospects for Peace," will take place Wednesday morning, April 20.

Inspection trips to the U. S. Naval Academy Experiment Station and to Aberdeen Proving Grounds will be on Friday, April 22.

Elliott Felt, Jr., chairman of technical events for the ARS sessions, announces the final program as follows:

Wed. Apr. 20, 2:30 p.m.
Rocket Test Vehicles

The Use of Rocket Vehicles for Upper Atmosphere Research—*J. W. Townsend*, Naval Research Laboratory.

Flight Measurements of Aerodynamic Heating and Boundary Layer Transition on the Viking 10 Nose Cone—*R. B. Snodgrass*, NRL.

Instrumentation Techniques and Requirements for Rocket and Guided Missile Testing—*H. B. Riblet*, Applied Physics Lab., Johns Hopkins Univ.

The Worthwhileness and Applications of a Minimum Orbital Unmanned Satellite of the Earth (MOUSE)—S. Fred Singer, Univ. of Maryland.

Thurs. Apr. 21, 9:30 a.m.
Instrumentation

Chairman: R. T. Franzel, Air Research and Development Command.

Vice-Chairman: George Johnson, ARDC.

Photography from the Viking 11 Rocket —*L. Winkler*, NRL.

Systems Engineering for Human Flight Control—*L. J. Fogel*, Stavid Engineering, Inc.

Jet Propulsion Pressure Measurements at Audio Frequencies—*H. B. Jones*, Princeton Univ.

Thurs. Apr. 21, 2:30 p.m.
Manned Rocket Vehicles

Chairman: W. A. Webb, Aircraft Armaments, Inc.

Vice-Chairman: Samuel Fradin, Miller Metal Products.

Rotor Rocket Development for Helicopters—*W. R. Brown*, Reaction Motors, Inc.

Some Practical Aspects of Rocket Powered Aircraft—*W. F. Moore* and *R. C. Smith*, Bell Aircraft Corp.

Optimum Climbing Technique for a Rocket Powered Interceptor—*Angelo Miele*, Polytechnic Inst. of Brooklyn.

Future Applications for Manned Rocket Vehicles—*C. L. Forrest* and *R. B. Crisman*, Bell Aircraft Corp.

Truax Announces Student Award Competition

COMMANDER Robert C. Truax, USN, chairman of the ARS Awards Committee, has sent notices to all of the Society's Student Members inviting their participation in this year's competition for the Annual Student Award.

Himself an active rocket experimenter while a midshipman at Annapolis in the late 1930's, Commander Truax was a recipient of the Robert H. Goddard Memorial Award for liquid propellant work in 1951.

Entries should be submitted to Commander Truax at 2924 N. Oxford St., Arlington, Va., prior to August 1. Papers in the general field of rocket and jet propulsion are invited. They will be judged on the basis of accuracy, expression, understanding of the subject presented, and original thought. There are no special requirements as to form, content, or length.

Winner of the competition will receive his award at the Annual Honors Night Dinner, to be held this year in Chicago on Nov. 16.

Four distinguished leaders in the rocket and guided missile field comprise this year's Awards Committee. Invited to serve by Commander Truax are Louis G. Dunn, associate director of the Guided Missile Division of Ramo-Wooldridge Corp.; Brig. Gen. H. N. Toftoy, commanding general of Redstone Arsenal; William E. Zisch, vice-president and general manager of Aerojet-General Corp; and Thomas F. Reinhardt of Bell Aircraft Corp.

New England Section Forming

SEVENTY-FIVE people attended an organizational meeting of a proposed New England Section on March 24.

Chairman of the meeting, which was held at the Massachusetts Institute of Technology Faculty Club in Cambridge, Mass., was Frederick C. Durant III of Arthur D. Little, Inc., ARS national president in 1953 and current president of the International Astronautical Federation.

Mr. Durant introduced James J. Harford, ARS Executive Secretary, who outlined the Society's objectives and history.

A provisional slate of officers was elected, pending approval of the Section's charter by the national Board of Directors. The officers include: C. Lincoln Jewett, Arthur D. Little, Inc., president; Joseph Kelley Jr., Allied Research Associates, vice-president; Kay Manion, ADL, secretary; and Alexis Pastuhov, ADL, treasurer. Chosen to serve as directors were John Logan, Cambridge Corp.; Bradford Darling, MIT faculty member; W. Saffer, National Ordnance Div., National Fireworks Corp.; H. Kasnitz, American Machine & Foundry, Electronics Div.; W. Sawyer, ADL; Leopold Michel, General Electric, Small Aircraft Gas Turbine Dept.; and Thomas Gibb, Tufts University.

The Glenn L. Martin Company film, "Horizons Unlimited," was shown.

ARS Meetings Calendar

		Theme
Apr. 18–22	ARS-ASME Spring Meeting, Baltimore	(See above)
June 19–23	ARS-ASME Semi-Annual Meeting, Boston	General
Aug. 1–6	Sixth IAF Congress, Copenhagen	
Aug. 22–24	ARS-Northwestern University Gas Dynamics Symposium, Evanston, Ill.	Combustion
Sept. 19–21	ARS Fall Meeting, Los Angeles	General
Nov. 13–18	ARS-ASME Annual Convention, Chicago	General

Papers for all of the above meetings, except the Spring Meeting, are invited. Abstracts or manuscripts should be submitted to the Program Chairman, American Rocket Society, 500 Fifth Ave., New York 36, N. Y. It is requested that abstracts be sent 120 days prior to the meeting date.

Section Doings

ARS SECTION PRESIDENTS

Alabama: Joseph Wiggins, *Thiokol Chem. Corp.;* **Arizona:** R. H. Hansen, *Hughes Aircraft Co;* **Central Texas:** B.S. Adelman, *Phillips Petroleum Co.;* **Chicago:** V. J. Cushing, *Armour Research Foundation;* **Cleveland-Akron:** John Sloop, *NACA;* **Detroit:** Laurence M. Ball, *Chrysler Corp.;* **Florida:** K. K. McDaniel, *Boeing Airplane Co.;* **St. Louis:** Norton B. Moore, *McDonnell Aircraft Corp.;* **Indiana:** A. R. Graham, *Purdue Univ.;* **Maryland:** W. G. Purdy, *Glenn L. Martin Co.;* **National Capital:** E. C. Page, *Page Communications, Inc.;* **New Mexico-West Texas:** R. C. Sherburne, *New Mexico A & M;* **New York:** C. W. Chillson, *Curtiss-Wright Corp.;* **Niagara Frontier:** T. Zannes, *Bell Aircraft Corp.;* **Northeastern New York:** Kurt Berman, *General Electric Co.;* **Northern California:** W. J. Barr, *Detroit Controls Corp.;* **Pacific Northwest:** R. M. Bridgforth, *Boeing Airplane Co.;* **Princeton Group:** Irvin Glassman, *Princeton Univ.;* **Southern California:** C. M. McCloskey, *ONR;* **Southern Ohio:** W. J. Mizen, *Bendix Aviation Corp.;* **Twin Cities:** J. J. Schons, *Univ. of Minnesota.*

Von Kármán at Southern California

THEODORE von Kármán, ARS Fellow and winner of the first Astronautics Award last year, spoke to 250 members at the IAS Building in Los Angeles at the February meeting.

Dr. von Kármán discussed the activities of NATO's Advisory Group for Aeronautical Research and Development, of which he is chairman.

***Southern California* vice-president R. D. Geckler introduces speaker Theodore von Kármán (right)**

A full report from Publicity Chairman E. A. Blair brings **Southern California** activities up to date. The "outstanding meeting of 1954" was a November 10 symposium at Thompson Laboratory, U. S. Naval Ordnance Test Station, Pasadena. A closed affair, the meeting was attended by 350 who heard a panel discussion of missile systems, including long range surface-to-surface ballistic types; medium surface-to-air; and short range air-to-air.

On the panel were C. E. Bartley and H. L. Thackwell of Grand Central Rocket; W. E. Campbell of Aerojet; R. B. Canright of Douglas; C. W. Cole of JPL; G. P. Sutton of North American; Quentin Elliott, Jerry Makepeace, and Robert Young.

The full slate of officers for 1955 is as follows: C. M. McCloskey of ONR, president; R. D. Geckler of Aerojet, vice-president; D. I. Baker of North American, secretary; A. D. Jamtass of Douglas, treasurer. Vacancies on the Board of Directors have been filled by J. J. Burke of JPL; T. F. Dixon of North American; R. F. Gompertz of Edwards AFB; W. M. Hawkins of Lockheed; W. C. House of Aerojet; and C. A. Weise, Douglas.

Retiring president H. S. Seifert hands gavel to new *Southern California* head, C. M. McCloskey

Solid Propellants—in Indiana and New York

Dr. H. W. Ritchey, technical director of the Redstone Division of Thiokol Chemical Corp. and winner of last year's C. N. Hickman Award, spoke on "Design Criteria of Solid Propellant Rockets" at an **Indiana** Section meeting on Jan. 25. The meeting took place at Purdue University.

Dr. Hickman, himself, spoke on solid propellant rockets before the **New York** Section's Jan. 21 gathering.

He reviewed the development work which went into the design of the bazooka, dating back to 1918. In World War II he began work on a rocket-assisted, low-altitude armor-piercing bomb for the Navy, and also helped in the development of a $4^{1}/_{2}$-in. rocket and long-range mortar shells.

Much of Dr. Hickman's work was done in collaboration with the late Dr. Robert H. Goddard. He showed slides and films

Three sections hear Dornberger on rocket-powered airliner

PHOTO CREDIT: Bernard Mollberg

Demonstrating a ubiquitousness which suggests that his pet project of the future—a rocket-powered airliner—might already exist, Dr. Walter R. Dornberger spoke at three widely separated ARS Section meetings recently.

The former V-2 chief, now a consultant on missile design to Bell Aircraft Corp., appeared before the **Florida** Section on Jan. 19, **Detroit** on Feb. 22, and **Cleveland-Akron** on Feb. 24. He is shown above (left) with L. X. Chapin, program chairman; Laurence M. Ball, president; and Lovell Lawrence, meeting chairman; all of Chrysler Corporation and the **Detroit** Section. Dornberger is the third from left.

At right he appears with the **Florida** Section's Jess Zabrieski of Bell Aircraft; Keith McDaniel of Boeing, Section president; and cartoonist Zack Mosley. This meeting attracted 250.

Dornberger predicts rocket-propelled airliners capable of 13,000 mph speeds within 15 years, London-New York travel in 75 minutes, San Francisco-Australia in 90 minutes. Powered flight will be for only a few minutes, most of the distance being covered by glide at extreme altitudes.

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__193-55 Flight Measurements of Aerodynamic Heating and Boundary Layer Transition on the Viking 10 Nose Cone, R. B. Snodgrass, Naval Research Laboratory

__194-55 Optimum Climbing Technique for a Rocket-Powered Interceptor, Professor Angelo Miele, Polytechnic Institute of Brooklyn

__195-55 The Worthwhileness and Applications of a Minimum Orbital Unmanned Satellite of the Earth (MOUSE), S. Fred Singer, University of Maryland

__196-55 Photography from the Viking 11 Rocket, L. Winkler, Naval Research Laboratory

__197-55 Instrumentation Techniques and Requirements for Rocket and Guided Missile Testing, H. B. Riblet, Applied Physics Lab., Johns Hopkins University

__199-55 Jet Propulsion Pressure Measurements at Audio Frequencies, Howland B. Jones, Consultant, Jet Propulsion Research Program, Dept. of Aeronautical Engineering, Princeton University

__200-55 Rotor Rocket Development for Helicopters, W. R. Brown, Reaction Motors, Inc.

__201-55 Some Practical Aspects of Rocket-Powered Aircraft, W. F. Moore and R. C. Smith, Bell Aircraft Corp.

__202-55 Future Applications for Manned Rocket Vehicles, C. L. Forrest and R. B. Crisman, Bell Aircraft Corp.

__203-55 Systems Engineering for Human Flight Control, L. J. Fogel, Stavid Engineering, Inc.

NAME..

ADDRESS ....

CITY.................................... STATE...............

C. W. Chillson, president New York Section, chats with Rudolph L. Graupe, Fairchild Engine & Airplane Co., Don B. Clark, Wright Aeronautical Division, and Charles G. Sage, ARDE Associates

of various rockets and launching devices and explained the operation of the proximity fuse.

Space Medicine and Steak

Erik Bergaust of the National Capital Section reports that physiologist and space medicine specialist S. W. Ames of the Air Force Surgeon General's office gave a talk on his field at a Feb. 8 meeting held in Washington's Aviation Club.

Fifty members and guests were taught a lot about acceleration problems and how the modern laboratory tries to solve them. Films of the Terrier, Sparrow, and Regulus were shown, a steak dinner was served, and Jim Patton walked off with the door prize, a model of Martin's B-61 Matador.

Are the Engineering Colleges Doing a Good Job?

A panel of four experts discussed the

question, "Are the Colleges and Universities Turning Out Adequately Trained Engineers?" at a Jan. 12 meeting of the Maryland Section.

Glenn L. Martin vice-president George Trimble held that more time should be given during college for art, music appreciation and such, in order to stimulate creative minds.

Francis H. Clauser, Chairman of the Dept. of Aeronautics at Johns Hopkins University, felt that management training could not be added to the present curriculum without affecting some other vital area.

The viewpoint of Joel M. Jacobson, vice-president of Aircraft Armaments, Inc., was that management training was the responsibility of industry and that training in the basic sciences should be broadened.

Ramjet Airliners Before 1975?

Donald B. Clark of Wright Aeronautical Division, Curtiss-Wright Corp., gave an interesting review talk on ramjets before a Feb. 18 meeting of the **New York** Section. About 80 people heard the talk which was illustrated with slides and a film, reports William A. Flynn

Clark pointed out the tremendous amount of work which was necessary in developing materials, pumps, burners, and control systems for the ramjet. He cited the engine's advantage in weight-hp ratio over piston and turbojet units.

He also foresaw the application of the ramjet to helicopters and commercial aircraft, predicting that the latter would take place before 1975.

Aerodynamic Heating Discussed at Indiana

The effect of aerodynamic heating on power plant and missile design was the

PHOTO CREDIT: Bernard Mollberg

Rocketeers on TV

Richard B. Morrison, chief of the University of Michigan's Rocket Propulsion Laboratory (center), and Maurice Brull of the U. of M. Aero. Dept. (right), locked horns with a pair of flying saucer believers in a television debate over Detroit's WJBK-TV recently, bearing the standards of the ***Detroit*** Section. It's reported that they won hands down, if it's possible to win in such an argument. At left is show's producer, Bob Murphy.

theme of a talk by Robert W. Bonner of Glenn L. Martin before a Feb. 23 gathering of the **Indiana** Section at Purdue University.

Slides and films of the Viking firings illustrated Bonner's points.

Missile Propulsion

Robert N. Oliver of the Propulsion Research Group at Convair spoke to an **Indiana** Section meeting at Purdue University on March 2.

The slide-illustrated talk was on "Integration of a Rocket Propulsion System into a Missile," reports James A. Bottorff.

Pino Elected

New president of the **Northern California** Section is M. A. Pino of California Research Corp., Richmond, Calif.

Other officers are A. J. Eggers, Jr., Ames Aeronautical Laboratory, NACA, vice-president; Commander E. A. Quarterman, USNR, treasurer; and Kenneth G. Heller, Detroit Controls Corp., secretary.

Elected to serve as a director until 1958 is Victor Stevens of Ames Aero Lab.

By-Laws of the American Rocket Society, Inc.

ARTICLE I

Section 1. The name of this Society shall be the American Rocket Society, Inc.

ARTICLE II

Section 1. The purpose of the Society shall be to aid and encourage by all suitable means the development and application of the principle of jet propulsion as applied to rockets, aircraft, water and underwater craft, and to all other appropriate and practical devices; to aid and encourage the development of the sciences and engineering techniques pertaining thereto, and to create increasingly wide interest in the field of jet propulsion and rocketry among both technicians and laymen, to the end that jet propulsion in all its various forms shall rapidly and permanently be developed for the good of man; the preparation, collection, correlation, and dissemination, by publication or otherwise, of facts, information, articles, books, pamphlets, and other literature pertaining to jet propulsion, rocketry, and subjects relating thereto; the establishment of a library containing such literature for the information of members, scientists, and others to whom the privileges of such library may be granted by the Society; the collaboration or affiliation with other organizations, whether technical or otherwise, in any manner, and to any extent which, in the judgment of the Society or of the Board of Directors, will best aid in accomplishing its objectives; the raising of funds for research and experimentation; and such other activities as the Society or the Board of Directors may from time to time deem necessary or desirable in connection with the foregoing.

ARTICLE III

Section 1. The membership of the Society shall comprise five classes, namely: (a) Fellow Members; (b) Members; (c) Associate Members; (d) Student Members; (e) Corporate Members.

Section 2. Fellow Members may be elected yearly by the Board of Directors from a list of persons who have distinguished themselves in the field of rocket or jet propulsion or who contributed outstanding service to the Society.

Section 3. Members shall consist of engineers and scientists who are actively engaged in the development or application of rocket or jet propulsion, other persons who have been working on the development or application of rocket or jet propulsion for at least four years and who hold or have held responsible positions in these fields, and such persons as may be deemed eligible for this class of membership by the Board of Directors by virtue of their outstanding accomplishments in other fields and their unusual interest in the purposes of the Society.

Section 4. Associate members shall consist of persons, other than students, who are actively interested in the development or application of rocket or jet propulsion.

Section 5. Student members shall consist of persons not less than 17 years of age whose principal occupation is study at a recognized educational institution or who are serving as enlisted personnel in the Armed Forces of the United States, and who are interested in the development or application of rocket or jet propulsion.

Section 6. Corporate Members shall consist of educational, scientific, or industrial organizations who may choose this method of expressing their interest in the development or application of rocket or jet propulsion, and who are considered acceptable by the Board of Directors. Each Corporate Member shall be entitled to five representatives with the rights and privileges of Members.

Section 7. A person (or organization) having expressed his (or its) desire for membership shall become a member of the appropriate class upon satisfaction of the Membership Committee as to his (or its) eligibility, sincerity of purpose, and good reputation, upon payment of dues as required by these By-Laws and upon approval of his (or its) application by the Board of Directors.

Section 8. Members of all classes shall be entitled to attend all business and other meetings of the Society except such meetings as may be designated in advance as closed to all persons without military security clearance. In addition, all classes of members shall be entitled to avail themselves of the Society's library, to receive Jet Propulsion, the Journal of the American Rocket Society, and other general publications of the Society, and to participate in other rights and privileges of the Society except as expressly provided herein.

Section 9. Subject to the provisions of the Section By-Laws, members of all classes shall be entitled to vote on matters related to the business of the Section to which they belong. Voting on all business of National Society shall be restricted to Fellows and Members. There shall be no vote by proxy, but votes may be cast by mail subject to provisions made elsewhere in these By-Laws.

Section 10. For conduct prejudicial to the objectives, reputation, or property of the Society, a member of any class may be censured, suspended, or expelled by a two-thirds vote of the Board of Directors after notice of the charges against him and of the time and place of the meeting at which they are to be presented, and an opportunity to be heard in his own defense. No person, having once been admitted in good faith as a Member of the Society, shall be denied the right to continued membership of the same class except for the above reasons and through the above procedure.

ARTICLE IV Dues

Section 1. The dues of Fellows and Members shall be Fifteen Dollars per annum, payable in advance. Any Fellow or Member may become a Life Member by making a single payment in accordance with the following table:

Age	Lump sum payment
25–30	$450.00
31–35	425.00
36–40	400.00
41–45	350.00
46–50	300.00
51–55	250.00
56–60	200.00
61 and over	150.00

Section 2. The dues of Associate members shall be Ten Dollars per annum, payable in advance.

Section 3. The dues of Student members shall be Five Dollars per annum, payable in advance.

Section 4. The dues of Corporate members shall be Two Hundred and Fifty Dollars, payable in advance.

Section 5. Each Section shall submit its annual budget to the Board of Directors on or before 31 December in each year. The Board of Directors shall, after approving such budget (either as submitted or as revised by it), allocate to the Section a portion of the dues received by the Society from the membership of such Section during the budget year, which portion shall be, for each class of membership, as determined by the Board of Directors from time to time.

ARTICLE V Sections

Section 1. The members of all categories in any city, state, or other geographical division, as determined from time to time by the Board of Directors shall constitute a local Section of the Society. Each Section shall elect its own officers and adopt such rules of procedure as it may, subject to the approval of the Board of Directors, determine. The Board of Directors may from time to time direct the division of a Section into one or more new Sections, the consolidation of two or more Sections, the transfer of members and territory from one Section to another, and such other changes in the territorial jurisdiction and membership of the Society as it shall deem advisable.

Section 2. Each Section shall submit its By-Laws to the Board of Directors for approval. Such By-Laws shall contain a provision that they are in all respect subject to, and that the members of the Section shall be governed by, the Certificate of Incorporation and the By-Laws of the Society. Upon approval of its application and completion of its organization, the Section shall receive a Charter from the National Office. By-Laws of Sections and amendments thereto shall at all times be on file at the National Office.

Section 3. The Sections shall concern themselves with furthering within their respective localities the purposes and program of the Society as set forth in these By-Laws and from time to time by the Board of Directors and by the Society.

Section 4. Each Section shall adopt as its name (insert name of city, state, or other locality) Section, American Rocket Society, Inc.

ARTICLE VI Meetings

Section 1. Annual meetings of the Society shall be held in November or December of each year, commencing with the year 1947, at a time and place to be determined by the Board of Directors.

Section 2. Special meetings may be

called by the President or any three of the Directors.

Section 3. Notice of all business meetings of the Society shall be sent by the Secretary to every Section at least thirty days in advance in the case of the annual meeting and fifteen days in advance in the case of special meetings.

Section 4(a). The Executive Secretary shall cause ballots for the election of the President, Vice-President, and Directors at each annual meeting of the Society and for voting upon such propositions as shall be submitted to any meeting of the Society for its decision to be prepared and mailed (or delivered personally) to every Fellow and Member not less than thirty days prior to the date of such meeting.

Section 4(b). Votes cast by mail at any meeting shall be addressed to the Executive Secretary at his official address as stated on the ballots. Only such votes as are delivered to him prior to the stated time of the meeting shall be received and counted; provided, however, that Members whose votes shall not have been cast by mail may vote in person at the meeting.

Section 4(c). All votes duly received by mail, together with those cast by Fellows and Members attending in person, shall be counted by tellers appointed by the President. The results shall be made known to those present, and may, at the discretion of the President, be printed in JET PROPULSION or otherwise conveyed to members absent from the meeting.

Section 4(d). Any proposition upon which the Board of Directors votes to obtain the consent, approval, or ratification of the Fellows and Members, apart from a meeting of the Society, may be presented to and acted upon by the Fellows and Members in accordance with the following procedure:

The Executive Secretary shall prepare and mail to each Fellow and Member a ballot setting forth in full the matter to be presented, the action, if any taken by the Board of Directors thereon, and a limiting date, not less than twenty days and not more than sixty days subsequent to the date when such ballot is mailed, on or prior to which the ballots must be returned. Only such ballots as are duly executed by the Fellows and Members and received by the Executive Secretary prior to the limiting date shall be counted by tellers appointed by the President prior to the limiting date and the results shall be made known by publication in JET PROPULSION or by written notice to the members.

Section 5. At any business meeting of the Society twenty or more Fellows and Members shall constitute a quorum for all purposes, except as otherwise provided by law. The act of a majority of the Fellows and Members present or voting by mail at any meeting at which a quorum is present shall be the act of the full membership except as may be otherwise specifically provided by statute or by these By-Laws. Whether or not there is a quorum at a meeting, the meeting may be adjourned from time to time by a vote of a majority of Fellows and Members present without notice other than by announcement at the meeting. At any adjourned meeting at which a quorum shall be present, any business may be transacted which might have been transacted at the meeting as originally notified.

Section 6. At all annual meetings of the Society, the order of business shall be as follows:

a. Roll Call
b. Reading of Minutes of Previous Meeting
c. Report of President
d. Report of the Board of Directors
e. Report of Treasurer
f. Other Reports

g. Election of President, Vice-President, and Directors
h. Unfinished Business
i. New Business

The foregoing order of business shall, insofar as practicable, be followed at all special meetings of the Society.

Section 7. Robert's "Rules of Order, Revised" shall govern the procedure at all meetings. Unless otherwise provided by statute or by these By-Laws, all elections and all questions shall be decided by a majority of the votes cast.

ARTICLE VII Board of Directors

Section 1. The governing body of the Society shall be a Board consisting of the President, the Vice-President, and nine Directors who shall be elected from the Fellows and Members at the annual meetings of the Society, as hereinafter provided. The Executive Secretary, Secretary, Treasurer, and the Editor-in-Chief of JET PROPULSION, if not elected Directors, shall be ex-officio members of the Board, and shall be entitled to attend all meetings and to take part in all discussions, but shall not be entitled to vote.

Section 2. At the annual meeting to be held in November or December, three new Directors shall be elected each year to serve for three years or until their successors are elected and qualified. At each such election, the three candidates receiving the highest number of votes shall be deemed elected.

Section 3. No Director shall serve for more than two consecutive terms.

Section 4. The President will normally act as Chairman of the Board of Directors. However, at the first meeting of the Board after the annual meeting of the Society, the President may declare himself unable to assume the Chairmanship of the Board, in which case the Board of Directors shall elect another of its members to be Chairman. Any member of the Board, including the Vice-President, shall be eligible to hold this position. In the absence of the regular Chairman at any meeting of the Board, the Directors shall designate a temporary Chairman to preside at the meeting.

Section 5. The first meeting of the Board of Directors shall be held as soon as is feasible after the conclusion of the election of new directors. Other meetings shall be held at reasonable intervals and, in any case, not fewer than four times each year. The President or Chairman of the Board shall submit an agenda in advance of the meeting dates so that each Director may become acquainted with the business at hand. The dates of the Board meetings shall be established at least thirty days in advance in order that the Directors may make their plans to attend.

Section 6. Five or more elected members of the Board shall constitute a quorum.

Section 7. In case of a vacancy in the Board of Directors, by death, resignation, or removal, the remaining members of the Board shall elect a Fellow or Member of the Society to fill the vacancy for the unexpired term.

Section 8. The Board of Directors shall cause minutes to be kept of their meetings and of all actions taken by them by which the Society may be bound or which involve expenditures of the funds of the Society. Such minutes shall be kept by the Secretary and it shall be the privilege of any Member in good standing to inspect the same at any reasonable time.

Section 9. The fiscal year of the Society shall end on 31 December of each year. The Board of Directors shall cause to be made and certified a report of the receipts and disbursements of the Society for the past fiscal year and an estimate of the receipts and disbursements of the current fiscal year, a true copy of which report and estimate shall be sent to each Section before the following annual meeting, together with the notice of such meeting.

Section 10. For conduct prejudicial to the objects, activities, or property of the Society a Director may be removed from office by a two-thirds vote of those present at any annual or special meeting of the Society, after notice of the charge against him and of the time and place of the meeting at which they are to be presented, and an opportunity to be heard in his defense.

Section 11. At all meetings of the Directors the order of business shall be as follows:

a. Roll Call
b. Reading of Minutes of Previous Meeting
c. Report of Executive Secretary
d. Report of Treasurer
e. Report of Standing Committees
f. Report of Special Committees
g. Election of officers (other than President and Vice-President)
h. Reading of Communications
i. Unfinished Business
j. New Business

Section 12. The Board of Directors, pursuant to Section 46 of the Membership Corporations Law of New York, shall present at each annual meeting a report, verified by the President and Treasurer, or by a majority of the Directors, showing the whole amount of real and personal property owned by the Society, where located and where and how invested, the amount and nature of the property acquired during the year immediately preceding the date of the report, and the manner of acquisition; the amount applied, appropriated, or expended during the year immediately preceding such date and the purposes, objects, or persons to or for which such applications, appropriations, or expenditures have been made; and the names and places of residence of such persons who have been admitted to membership in the Society during such year, which report shall be filed with the records of the Society and an abstract entered in the minutes of the proceedings of the annual meeting.

Section 13. The Board of Directors may from time to time authorize the bestowal of any appropriate honors or recognition in the name of the American Rocket Society to any persons whom the Board may deem deserving.

ARTICLE VIII Officers

Section 1. The officers of the Society shall consist of a President, a Vice-President, Executive Secretary, Secretary, Treasurer, and such other officers as from time to time shall be appointed by the Board of Directors.

Section 2. Every Fellow and Member in good standing shall be eligible for office.

Section 3. The President and Vice-President shall be elected at each annual meeting. The remaining officers shall be appointed by the Board of Directors.

Section 4. Every officer, except the Executive Secretary and Secretary, shall serve for one year or until his successor is elected and qualified. Every officer, except the President and Vice-President, shall be subject to removal at any time, with or without cause, by a two-thirds vote of the Board of Directors. No President, having served a full term, shall be eligible for re-election until at least one year after expiration of such term.

Section 5. If there shall be a vacancy in the office of President, the Vice-President shall exercise his duties until the next annual meeting of the Society. If there are vacancies in the offices of both President and Vice-President, the Board of Directors shall elect a new President to serve until the next annual meeting. A vacancy in any other office shall be filled by the Board of Directors.

ARTICLE IX Duties of Officers

Section 1. It shall be the duty of the President to preside at all principal functions of the Society, except meetings of the Board of Directors if the Chairman of the Board is other than the President; to represent the Society in dealings with outside agencies, and to transact business in behalf of the Society as directed by the Society or its Board of Directors and in accordance with these By-Laws.

Section 2. It shall be the duty of the Vice-President to act in the place of the President in any case of his failure or inability to act; at the direction of the President to transact any business that would be in the power of the President to transact, and, in the case of death or disability of the President, for any reason, to serve out his term as President.

Section 3. The Executive Secretary, in conjunction with and under the direction of the Chairman of the Board of Directors, shall supervise the execution of all Society activities, the establishment of new Sections, the promotion of membership, the solicitation of advertising in all Society publications, and enlist the support of industry, Government, education, the public and all other agencies in whatever manner is deemed appropriate by the Board of Directors.

The Secretary, subject to the over-all supervision of the Executive Secretary, shall manage and administer all routines, procedures, finances, and personnel of the National Office, as well as arrange for all publications, meetings, conventions, and exhibitions, and record the proceedings of business meetings of the Society and of the Board of Directors.

The Executive Secretary and the Secretary shall be sworn to the faithful discharge of their duties and a record of the oath shall be made upon the records of the Society.

The Executive Secretary and Secretary shall be appointed by the Board of Directors and shall serve at the pleasure of the Board, provided that the Board in its discretion may contract for their services for a fixed period, during which they shall not be removed from office except for cause. They shall be paid such salary or other compensation for services as the Board of Directors, by a two-thirds vote, shall from time to time determine. They shall be aided in their work by a paid staff, including such employees and at such salaries as shall be approved by the Board of Directors.

Section 4. It shall be the duty of the Treasurer to collect all dues and assessments, to care for the funds of the Society, to make all financial reports as required by these By-Laws and to make such expenditures as are authorized by the Board of Directors of the Society. If required by the Board of Directors, the Treasurer shall give surety bond for the faithful discharge of his duties, the cost of such bond to be paid by the Society.

ARTICLE X Nominating Committee

The Nominating Committee shall be composed of the immediate past national President and immediate past Presidents of all local Sections which were in existence at the time of the last annual meeting. Newer Sections shall not be represented. Local Sections may elect an alternate representative if the past President is unwilling or unable to serve. Two-thirds vote of the Nominating Committee shall be required to validate the slate; this vote may be registered by telephone, telegraph, mail, or any other means, at the discretion of the Chairman.

The number of nominees for Directors in each case shall exceed by at least fifty per cent the number to be elected. Any Section may independently nominate one or more candidates for President, Vice-President, or Director provided advice thereof is given the

Secretary not later than sixty days before the date of the annual meeting. The notice of the annual meeting shall set forth the names of all nominees, specifying in each instance if they have been nominated independently by one or more Sections.

ARTICLE XI Other Committees

Section 1. In addition to the Nominating Committee, the Standing Committees shall consist of the following: (a) Executive Committee; (b) Policy Committee; (c) Membership Committee; (d) Awards Committee; (e) Finance Committee; (f) Program Committee.

Section 2. Special committees may be authorized at any time under the direction of the Board of Directors. Appointments thereto will be made by the Chairman of the Board.

Section 3. The Executive Committee shall consist of the Chairman of the Board of Directors, the Secretary, the Executive Secretary, the Treasurer, and three other members of the Board. The latter shall be designated by the Board and may be replaced at any time by action of the Board. The President is an ex-officio voting member. The Editor-in-Chief is an ex-officio nonvoting member. The Executive Committee shall meet on call of the Chairman or any two members of the Committee.

The Executive Committee shall exercise the powers and functions of the Board of Directors except as follows:

(a) It shall not have the power to amend these By-Laws or to make new appropriations in excess of $500 for any one item, or to remove any officer of the Society.

(b) Minutes of each meeting of the Executive Committee shall be kept and copies mailed to each member of the Board within one week. Objection within thirty days on the part of the Executive Committee shall render such action void and shall automatically place it on the agenda of the next Board meeting. This provision may be waived by a majority vote of the Directors, polled by telephone or telegraph at the discretion of the Executive Secretary.

Section 4. The Membership Committee shall pass on all applications for membership and make recommendations thereon to the Board of Directors or the Executive Committee. With the assistance of the Executive Secretary it shall also be responsible for conducting new membership campaigns and for the encouragement of groups seeking to form new Sections of the Society.

Section 5. The Finance Committee shall aid the Treasurer in preparation of budgets, investigate financial problems, including those related to the reinvestment of Society funds, and make recommendations to the Board of Directors. In the absence of fraud, no Director or member of the Finance Committee shall be liable for loss or damage resulting to the Society in connection with the retention, investment, or reinvestment of the funds of the Society.

Section 6. The Policy Committee shall consist of the President, Executive Secretary, and the Editor-in-Chief of Jet Propulsion and such other members as the Chairman may appoint. The latter need not necessarily be members of the Board of Directors. It shall be the duty of the Policy Committee to make recommendations to the Board on matters pertaining to the objectives of the Society.

Section 7. The Awards Committee shall seek candidates for the various awards of the Society, discuss the qualifications of these men, and recommend to the Board of Directors their choice for the various awards.

Section 8. The Program Committee shall arrange the programs of all National meetings and select the papers to be presented at such meetings. They shall recommend

sites for the meetings to the Board of Directors.

Section 9. The President shall be an ex-officio member of all committees except the Nominating Committee. The Chairmen of all standing committees, except the Nominating Committee, shall be appointed by the Chairman of the Board of Directors as soon as possible after the annual meeting of the Society and shall serve one year or until their successors are appointed and qualify.

ARTICLE XII Checks, Drafts, Notes, Securities

Section 1. Checks, drafts, notes, and orders for payment of money of the Society shall be drawn and signed by such officer or officers, employee or employees of the Society as may be authorized from time to time so to do by the Board of Directors.

Section 2. Any brokerage firm may be authorized to effect purchases, sales, or other transactions in securities on behalf of the Society upon the joint order of any two of the following: viz., the President, the Vice-President, Executive Secretary, and Treasurer.

ARTICLE XIII Prohibition Against Sharing in Earnings

No member, director, officer, or employee of, or member of a committee of, or person connected with, the Society, shall receive at any time any of the net earnings or pecuniary profits from the operation of the Society (provided that this shall not prevent the payment to any such person of such reasonable compensation for services rendered to or for the Society in effecting any of its purposes as shall be fixed by the Board of Directors), and no such person or persons shall be entitled to share in the distribution of any of its assets or property upon the dissolution of the Society. All members of the Society shall be deemed to have expressly consented and agreed that upon such dissolution or winding up of the affairs of the Society, whether voluntary or involuntary, the assets and property of the Society then remaining in its hands shall be distributed and paid over to such educational or scientific institutions or organizations, upon such terms and conditions, and in such amounts and proportions, as the Board of Directors may determine, to be used by the institutions or organizations receiving them for the purposes similar or kindred to those set forth in the Certificate of Incorporation of the Society as then amended.

ARTICLE XIV Amendments

Section 1. These By-Laws may be amended at any regular or special meeting of the Board of Directors by the affirmative vote of at least two-thirds of the Board, provided that notice of any proposed amendment shall be given to each Director at least ten days before the meeting at which it is to be considered, and provided further that no amendment so made, respecting the number of members of the Board of Directors, the method of their election, or the powers of the Board shall become effective until it has been ratified by a majority of the Fellows and Members of the Society, voting either in person or by mail. Amendments may also be effected by a majority vote (by Fellows and Members voting in person or by mail) at any annual or special meeting of the Society provided that notice of any proposed amendment shall be mailed or personally given to each Fellow and Member at least thirty days before the meeting at which it is to be considered.

Section 2. Amendments may be proposed to the Board of Directors by any three directors or to any meeting of the Society by any twenty Fellows or Members. The Executive Secretary shall give or mail notice in accordance with the foregoing provisions, of any amendments proposed to a meeting of the Society.

Book Reviews

C. F. Warner, Purdue University, *Associate Editor*

Aerodynamics: Selected Topics in the Light of Their Historical Development, by Theodore von Kármán, Cornell University Press, 1954, 203 pp. $4.75.

Reviewed by B. A. Reese
Purdue University

Dr. von Kármán has written a very readable and informative volume which presents a brief account of the main principles of the science of aerodynamics and the historical development of aerodynamic thinking. The author has known personally many of the important contributors to the development of the science of aerodynamics; consequently, he was able to tell many interesting details of the personalities and personal conflicts of these scientists, in addition to outlining clearly their contributions.

After a brief review of aerodynamic research before the era of flight, the book covers briefly the subjects of lift, drag and skin friction, supersonic aerodynamics, stability and aeroelasticity, and the period from the propeller to the space rocket. With such a breadth of subject material it is remarkable how much technical information has been included in this short book, and even though it will not add specifically to the technical knowledge of the practical engineering student, it should be very helpful in improving his perspective of the science of aerodynamics and hence his understanding. I feel the book should be read by all students of aerodynamics and should be required reading for all teachers of aerodynamics and related fields.

Strength and Resistance of Metals, by J. M. Lessells, John Wiley and Sons, Inc., New York, 1954, 450 pp. $10.

Reviewed by C. S. Cutshall
Purdue University

The design of machine elements depends not only on theoretical relations involving loads and internal stresses but also on information concerning the manner in which materials behave under stress. The aim of the author of this book, as stated in the preface, is to provide the senior and graduate student as well as the design engineer with information on the behavior of metals under stress as revealed by workers in the field. Much of this information is drawn from the author's many years of experience in different fields of mechanical engineering. Although most of the discussion is based on the behavior of steel, mention is also made of nonferrous alloys and cast iron.

In carrying out his aim, the author brought together in one volume a large amount of useful and pertinent information. The book begins with a chapter on the tensile test and its use as an acceptance test, including a discussion of the significance of true stress-strain characteristics. This is followed by a discussion of the mechanism of overstrain, hysteresis effects, residual stresses, and behavior of metals at high temperatures. Chapter 4 takes up hardness and its importance in the control of materials, following which is a chapter on impact and the engineering significance of the energy-absorbing capacity of elements subjected to impact. Chapters 5 and 6 deal with fatigue including a general description of fatigue phenomena, the relation of fatigue strength to tensile strength, the effect of mean stress on fatigue strength, and a discussion of the many variable factors that influence fatigue. Many examples of actual fatigue failures are described. Strain hysteresis and damping are considered in Chapter 9. Mechanical wear and theories of friction are covered in Chapter 10, and the book concludes in Chapter 11 with a discussion of the more important theories of strength and the subject of working stresses.

Among the distinctive features of the book are the numerous references to sources of information, a generous supply of illustrative problems, and a large number of additional problems at the end of the book bearing on the subject matter of each chapter. These should be of considerable value to both student and designer.

The material presented is primarily descriptive rather than mathematical in character and should be readily comprehended by anyone with a knowledge of the elements of strength of materials. It is the opinion of this reviewer and colleagues whom he has consulted that the book represents an outstanding and much needed contribution to its field.

Vibration Problems in Engineering, by S. Timoshenko, 3rd edition in collaboration with D. H. Young, D. Van Nostrand Co., Inc., New York, 1955, 468 pp. $8.75.

Reviewed by B. E. Quinn
Purdue University

It is interesting to see the changes that have been made in this classic as a result of the increased interest in vibration problems and the developments that have occurred in this field. The authors have recognized that the subject of instrumentation has expanded enormously since the second edition (1937) and they have wisely given references where this subject arises, but have omitted the detailed description of instruments that were included in the previous editions. There has also been a considerable rearrangement of the material that has been retained, thus permitting the introduction of many more problems and new developments in vibration theory.

Of particular interest to many engineers is the elimination of Lagrangian equations in the solving of vibration problems. The name of Lagrange does not even appear in the author index! According to the preface "—all derivations are based on the more familiar d'Alembert's principle—" although on page 2 the use of Newton's principle is stated and described. It isn't until page 196 that the inertia forces and couples, usually associated with d'Alembert's principle, are introduced. On intervening pages the equations of motion are

(*Continued on page 196*)

Technical Literature Digest

M. H. Smith, *Associate Editor,* **and M. H. Fisher,** *Contributor*
The James Forrestal Research Center, Princeton University

Jet Propulsion Engines

Technical Aspects of Thrust Reversal, by George Curiel, *Aeroplane,* vol. 87, Nov. 12, 1954, pp. 696–697.

Gas Dynamics Research in Engine Development, *De Havilland Gazette* no. 183, Oct. 1954, pp. 110–115.

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Book Reviews

(*Continued from page 192*)

sometimes obtained without the benefit of free body drawings and without indicating the procedure being used. In this respect there is some confusion concerning the process whereby the differential equations of motion are obtained.

After the equations have been obtained, however, a complete treatment of the problem follows, as is characteristic of all the books by S. Timoshenko.

Chapter I of the third edition contains many more problems than earlier editions. A more extensive treatment of the transient state of forced vibrations is given together with more information on damping. Certain details concerning rotor balance have been omitted, but the section dealing with periodic disturbing forces has been enlarged. A phase-plane construction for determining the response of a system under the influence of a nonperiodic force has been added, together with sample problems.

Chapter II contains the information formerly covered in chapters II and III of the previous edition (nonlinear systems and systems with variable spring characteristics). There is more information on free vibration of systems with nonlinear restoring forces, and application is made of the Ritz method to forced, nonlinear vibration problems. A section has been added dealing with the instability of systems with variable spring characteristics, but the discussion of stability of steady-state motion (in the second edition) has been retained. A large amount of the detail pertaining to the locomotive side rod drive problem has been deleted to accommodate the new material.

Chapter III (the first part of Chapter IV of the previous edition) has been purged of all references to Lagrange and his famous equations. Gone also is the discussion of generalized coordinates and generalized forces. This material has been replaced by a very lucid analysis of systems having two degrees of freedom. To those whose association with Lagrange has been only casual this will be a most welcome change.

The same method of analysis used in the previous chapter is applied to systems with several degrees of freedom in Chapter IV. The major portion of this chapter, however, deals with torsional vibration in multimass systems. The use of Grammel's tables to solve torsional vibration problems is included for the first time in this chapter.

The last chapter of the book (Chapter V) is comparable to Chapter VI in the second edition and contains a wealth of information on the vibration of elastic bodies. Again, more problems have been introduced and the chapter has been revised to permit the use of d'Alembert's principle and the principle of virtual work in place of Lagrangian equations. A new section has been added dealing with the vibrations produced by a prescribed motion of some cross section of a bar. Recent developments in the numerical computation of lateral frequencies of beams have been included (i.e., Myklestad's method) as well as information concerning the coupled bending and torsional vibration of beams.

The appendix, dealing with vibration measuring instruments, has been omitted in this edition. There are forty-nine new references in the author's index, although some of the names contained in the second edition have been dropped. Many engineers will find this book easier to read as a result of the revision, and will discover more techniques for applying vibration theory to actual problems.

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